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FUTURE EXPLORATION OF VENUS (POST-PIONEER VENUS 1978)

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16. Abstract

A comprehensive study was performed to determine the major scientific unknowns about the planet Venus to be expected in the post-Pioneer Venus 1978 time frame. Based on those results the desirability of future orbiters, atmospheric entry probes, balloons, and landers as vehicles to address the remaining scientific questions were studied. The recommended mission scenario includes a high resolution surface mapping radar orbiter mission for the 1981 launch opportunity, a multiple-lander mission for 1985 and either an atmospheric entry probe or balloon mission in 1988. All the proposed missions can be performed using proposed Space Shuttle upper stage boosters. Significant amounts of long-lead time supporting research and technology developments are required to be initiated in the near future to permit the recommended launch dates.

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FOREWORD

This report is the culmination of a six-month (January-July 1975) in-house study requested and supported by the Planetary Programs Office (Code SL) of the Office of Space Science (Code S) at NASA Headquarters. Thirty research scientists and engineers participated in the study, all on a part-time basis. The research scientists involved, drawn mainly from the Space Science Division, served on one or more study teams (Chart I). Those participants associated with mission and engineering aspects were drawn from the System Studies Division (Chart II). As part of the study, a distinguished scientific board of review (Chart III), intimately acquainted with planetary exploration, was convened at Ames on June 12, 1975, to critically review our conclusions and recommendations. However, the report should not be construed as an endorsement by the review board of our recommendations. The authors accept full responsibility for the contents herein.

The purposes of the study were to:

(1) Isolate the major scientific questions concerning the planet Venus which would remain following the Pioneer Venus missions ending in August 1979.

(2) Recommend a sequence of follow-on spacecraft missions to Venus for the 1980's.

(3) Recommend areas for early initiation of long lead-time and spacecraft engineering development and mission analyses.

The first purpose was addressed in several consecutive steps. First, we outlined the goals of planetary exploration and determined the role Venus exploration plays toward the fulfillment of these goals. Second, we developed a comprehensive list of exploration objectives therefrom, appropriate to the Venus ionosphere, atmosphere, clouds, surface, and interior. Then we surveyed in detail the current (1975) state of knowledge of Venus. Next we attempted to assess critically the contributions expected from the next five years of Earth-based radar and optical observations and from Pioneer Venus. A combination of the last two steps led directly to our first study purpose. (We did not place much emphasis on any forecasts of Soviet contributions which are highly probable, given the Venus launch opportunities of June 1975 and January 1977. Periodic reassessments of our findings are desirable, certainly following any future Soviet missions.)

As a point of departure toward addressing the second study purpose, we studied the technological and instrumental feasibility, effectiveness, and uniqueness of particular spacecraft types: orbiters, entry probes, balloons, and landers. Combinations of these platforms for recommended missions were accomplished in the final study phase. The current NASA Planetary Programs Mission Model (dated February 18, 1975) includes the following missions to Venus:

(1) Pioneer Venus - approved mission with two launches in 1978.

CHART I.- STUDY TEAMS

	Orbiter	Atmospheric probe	Lander	Balloon
Blanchard, M.			X	
Borucki, W.		X		X
Cassen, P.	X			X
Colin, L.	X	X	X	X
Cuzzi, J.	X	X		X
Dyal, P.	X			
Gault, D.	X		X	
Giver, L.	X	X		X
Greeley, R.	*		X	
Linlor, W.	X			
Oberbeck, V.	X			
Quaide, W.			*	
Ragent, B.		X		
Reynolds, R.			X	
Seiff, A.		*		X
Sommer, S.		X		
Starr, W.	X			
Swift, C.				X
Whiting, E.		X		
Whitten, R.	X			
Woeller, F.			X	
Young, R.	X	X		*
22	12	9	7	8

*Chairman

CHART II.- MISSIONS AND ENGINEERING GROUP

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L. Evans, Asst. Study Leader
R. Jackson, Lander Design
L. Manning, Trajectories
R. Schaupp, Systems Analysis
B. Swenson, Consultant

CHART III.- SCIENTIFIC REVIEW PANEL

V. Eshleman	Stanford University
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J. Hansen	Goddard Institute for Space Studies
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W. Kaula	University of California at Los Angeles
C. Leovy	University of Washington
J. Lewis	Massachusetts Institute of Technology
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R. Prinn	Massachusetts Institute of Technology
R. Reynolds	Ames Research Center
A. Young	Texas A & M
V. Suomi*	University of Wisconsin
G. Schubert*	University of California at Los Angeles

*Written comments only.

(2) Venus Orbital Imaging Radar (VOIR) - two launches in 1983 (new start FY 81).

(3) Venus Large Lander - no launch year indication (see below).

This mission model was established as the result of studies in 1974 by the Committee on Planetary and Lunar Exploration (COMPLEX) of the National Academy of Sciences' Space Science Board (Opportunities and Choices in Space Science, 1974, published in 1975). The COMPLEX/NAS report recommended the sequence indicated above, with a reference to the third mission as an "undefined surface probe mission" with a launch date "later than 1987."

Earlier comprehensive studies of Venus exploration science objectives (Venus - Strategy for Exploration, Report of a Study by the Space Science Board, National Academy of Sciences, June 1970) also considered lander and balloon missions, but concentrated primarily on the scientific objectives of what was destined to become Pioneer Venus as a new start in FY 75. Since the 1970 study, we have had the Mariner 10, Veneras 7 and 8 missions encountering Venus (with 9 and 10 on their way), the selection of experiments for Pioneer Venus, and the introduction of the VOIR concept. This latter concept, requiring a three-axis stabilized Mariner-Class spacecraft as it is being planned currently by JPL, received careful scrutiny in our study. A spin-stabilized Pioneer-Class version of an orbiting radar mapper was also investigated. The Pioneer-Class spacecraft only was considered as a base for future entry probe, balloon, and lander missions.

The final study purpose hopefully will accomplish two things. First, Supporting Research and Technology (SRT) funds <u>must</u> be made available at an early stage if a viable, progressive planetary exploration program is to result. Secondly, long-held, nonproductive myths must be recognized and buried. Of prime importance is the myth of "off-the-shelf" experimental hardware. Such hardware does not exist today (if ever), and our efforts are becoming so sophisticated that new techniques and concepts are a must for future programs, particularly as we progress from reconnaissance-type to true exploration-type missions.

Finally, I would like to thank very sincerely and acknowledge the contributions of those who participated in the study. The perserverance and dedication evidenced was gratifying, particularly in view of the obvious lack of any significant near-term personal payoffs.

Lawrence Colin, Study Leader

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1.0 INTRODUCTION

Why explore Venus? The answer to that question is, of course, nested in the response to the more encompassing question: Why explore the solar system? The classic response justifying exploration is the very viable Hillary-Everest retort: "Because it's there!" For most scientists, this response is very satisfying, and little more need be said, especially for something like a mountain-climbing expedition that is largely self-supporting. For space exploration, however, much more needs to be said, particularly to a society that foots the not-insignificant bill. NASA and its associated scientists have not always been totally successful in providing acceptable justification for its exploration program. Yet we must continue to try, and our arguments must be credible to society at large. To this end, we must learn how to make our message clear, and we must educate society to better understand what we are saying.

For a report such as this, the task is a good deal simpler, for the intended reader is scientifically and/or aerospace-technology oriented. However, we must still address the same questions, for the orchestration of future mission scenarios associated with the exploration of Venus must and should contend with the major unknowns regarding that mysterious planet.

1.1 Planetary Exploration Goals

The fundamental goal of solar-system exploration is to provide knowledge concerning the origin, evolution, and present state of the bodies within that system, the atmospheres of the planets and satellites, and life. For the purposes to which such knowledge will be put, it is important to be able to isolate origins from evolution. The planets of the solar system, as we know and understand them today, are more noted for their differences than for their similarities. It is important to ascertain whether these differences result from different conditions of origin or from divergent paths of planetary evolution. It is important to determine whether the various atmospheres are primitive or secondary and in what state of development they currently exist. Only then can we discuss the existence of life on other planets, in the past and for the future.

These questions have fostered two very important subpurposes of solar-system exploration: comparative planetology and comparative meteorology. Much more will be said below about these subjects with respect to Venus and the terrestrial planets. Suffice it to say here that only when we have determined where we have been and how we have reached the present state (origin and evolution) can we on Earth say where we are heading. Man is busy polluting and altering his biosphere with unknown consequences. The future of man on Earth (and even on other planets, considering the potentials of planetary engineering) may well be written in the unique features of other planetary laboratories.

The importance of the questions of origin and evolution leads naturally, but not easily, to a specific set of basic questions applicable to any of the

planetary bodies. The NASA "Outlook for Space: 1980-2000" (to be published) contains such a set (reproduced in table I) prepared by W. C. Phinney. With these questions in mind, we can take the next step and inquire how Venus exploration fits into the scheme of things.

TABLE I.- SOME BASIC QUESTIONS FOR STUDY OF PLANETARY BODIES
(W. C. Phinney)

- How did body form?
  - Condensation and precipitation processes
  - Nature of accretion
  - Gas present as atmosphere
  - Fissioned from large body
  - Captured from another orbit
- Where did body form?
  - Present orbit
  - If elsewhere, where?
- When did body form?
- What modifications have occurred since formation by interactions with other bodies?
  - Impacts by solids on surface
  - Radiation effects
  - Field effects
- What was initial temperature distribution in the body?
  - Uniform throughout
  - Continuous gradient
  - Discontinuous distribution
- How has thermal gradient changed with time?
- What were initial chemical and isotopic compositions and how were they distributed?
  - Homogeneous solid
  - Random variation in solid
  - Systematic variation in solid
  - Atmospheric distribution
- Did body ever undergo chemical fractionations?
  - Large-scale layers (core, mantle, crust)
  - Effect on atmosphere
  - Local volcanic centers
- When did chemical fractionations occur?
  - Once
  - Periodically
  - Continuous
- What processes produced chemical fractionations?
  - Large-scale melting
  - Partial melting
  - Volatilization
  - Crystal fractionation
  - Diffusion
  - Viscous flow
- What modifications of chemical and isotopic compositions by external sources?

TABLE I.- SOME BASIC QUESTIONS FOR STUDY OF PLANETARY BODIES
(W. C. Phinney) - Concluded

How did atmosphere evolve?
Changes in composition
Nature of circulation
Interactions with surface
Is there evidence of organic precursors to living organisms?
Did living organisms ever exist?
Evolutionary sequence
Distribution
Can future trends of body be predicted?

1.2 Venus Exploration Goals

We deal extensively with the knowns and unknowns of Venus in later sections. However, a brief review of Venus as a participant in the solar system and as a terrestrial planet is presented here to establish its perspective with respect to scientific objectives.

1.2.1 Venus in the solar system - The planet Venus, named for the goddess of love and beauty, is the brightest of the five "naked-eye" planets (Mercury, Venus, Mars. Jupiter, and Saturn). It is the most brilliant object in the sky, except for the Sun and Moon; as a result, it has been known almost from the dawn of history (ref. 1). Its brilliance is not due to its size, but to its relative proximity and its efficient reflection of visible solar radiation.

The orbit of Venus lies wholly within that of Earth (fig. 1) and Venus therefore exhibits phases like Mercury and the Moon (refs. 2 and 3). Consequently, during its synodic period, it appears to swing back and forth in the sky, from one side of the Sun to the other. Thus it appears sometimes as an "evening star" (west) and sometimes as a "morning star" (east). At inferior conjunction (closest approach to Earth, approximately 0.28 AU), its angular size reaches some 64 seconds of arc. The planet is then new (dark) and therefore not observable. Near superior conjunction (farthest distance from Earth), it subtends an angle of some 10 seconds of arc, and, although full, it is not at maximum brilliance because of its large distance. Being close to the Sun, it is difficult to see. At greatest elongation (west or east), the planet is some 48° from the Sun, is some 39 seconds of arc in size, and its crescent exhibits maximum brilliance (stellar magnitude -4.4).

Table II contains comparative orbital and physical data concerning Venus, Earth, and Mars (refs. 3-5). Venus has been called Earth's "twin," for they resemble each other in several ways: Venus' radius, surface area, mean density, gravitational acceleration, and escape velocity are all within 90-95 percent that of Earth. Venus' mass is some 81.5 percent that of Earth. However, they are "nonidentical" in other more interesting ways. Venus' direction of rotation about its axis is retrograde (east to west), that is, it rotates opposite the Earth's rotation. The reason for this is unknown. The tilt of its axis is only 6° from the normal to its orbit plane, compared with 23.5° for Earth, and less than 3° from the normal to the ecliptic. This fact,

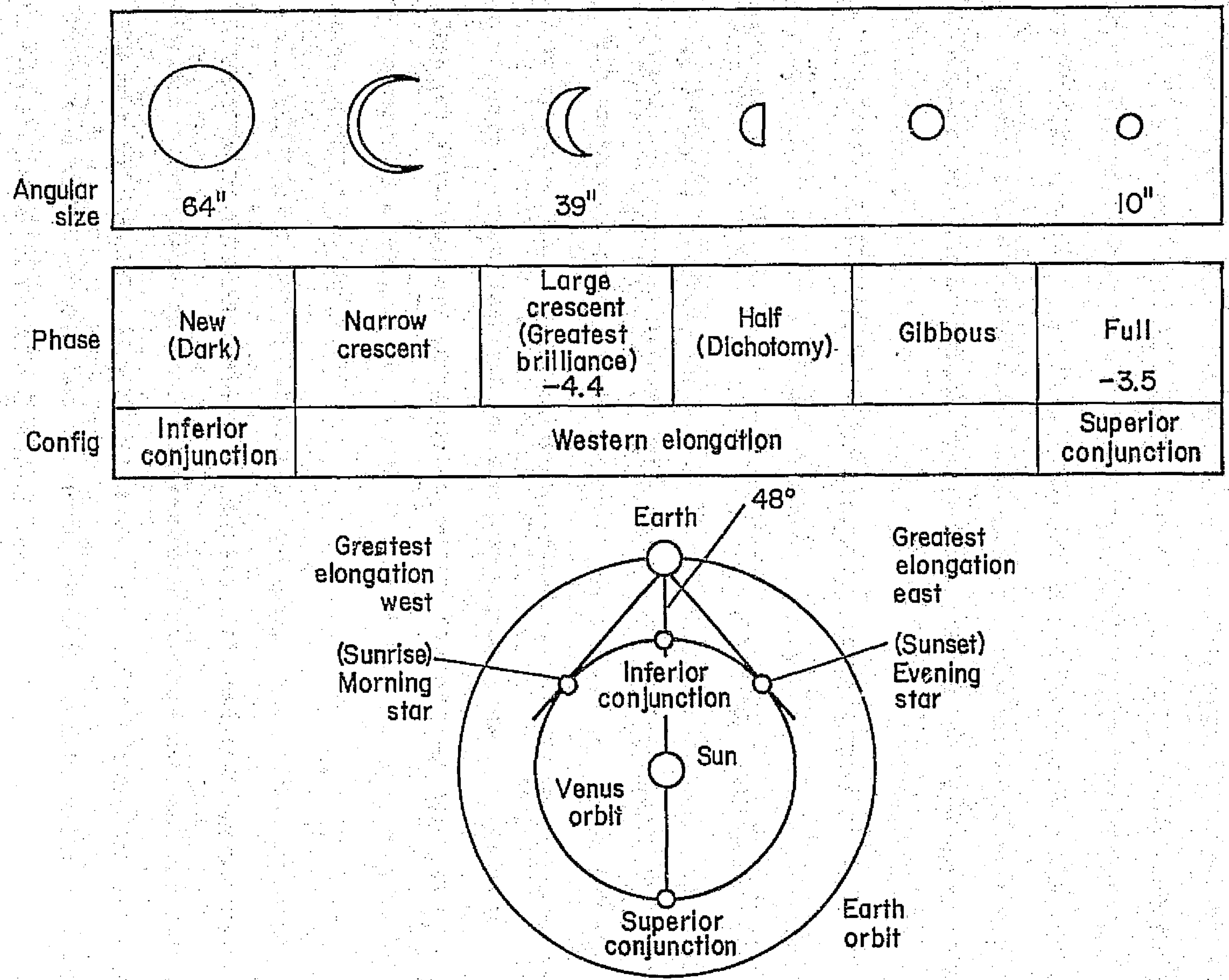


Figure 1.- Phases of Venus.

TABLE II.- PHYSICAL DATA FOR MARS, EARTH, AND VENUS

Parameter	Mars	Earth	Venus
Distance from Sun, AU (10^6 km)			
Mean	1.524 (228.0)	1.000 (149.6)	0.723 (108.2)
At perihelion	1.381 (206.6)	0.983 (147.1)	0.718 (107.4)
At aphelion	1.666 (249.2)	1.017 (152.1)	0.728 (108.9)
Orbit eccentricity	0.0933	0.0167	0.0068
Orbit inclination, deg	1.85	0.00	3.39
Mean orbital velocity, km/sec	24.13	29.75	35.05
Distance to Earth, inf. conj., AU (10^6 km)	0.38-0.67 (56.8-100.2)	---	0.27-0.29 (40.4-43.4)
Synodic period, Earth days	780	---	584
Sidereal period (year), Earth days	687	365	225
Rotation period (day), Earth days	1.026	1.000	-243.0
Solar day, Earth days	1.026	1	116.8
Direction of rotation	Direct	Direct	Retrograde
Obliquity (rot. axis tilt), deg	25.2	23.5	174
Mass, relative to Earth (10^{26} gm)	0.108 (6.46)	1.000 (50.8)	0.815 (48.8)
Mean radius, km	3380	6371	6050
Mean density, gm/cm^3	3.94	5.52	5.26
Gravitational acceleration, cm/sec^2	367	981	877
Escape velocity, km sec^{-1}	5.0	11.2	10.3
Solar radiation flux, 10^6 ergs cm^{-2} sec^{-1}	0.6	1.4	2.6
Albedo	0.15	0.39	0.71
Visual magnitude	-2.8	-3.8	-4.4
Effective temperature, °K	216	253	244
Satellites	2 (Phobos, Diemos)	1 (Moon)	0

*1 AU = 1.496×10^8 km = 93×10^6 miles

combined with the small orbit eccentricity (0.0068) compared to Earth (0.0167), suggests that seasonal effects, so prominent in the Earth's atmosphere, should be absent on Venus. Since it is closer to the Sun than Earth, thus having a higher orbital velocity, Venus' year is only 225 Earth days in duration. Its rotation period, 243 times that of Earth, is quite slow. This peculiar combination of orbital and rotational motions results in a solar day on Venus lasting some 117 Earth days. The synodic period (time interval between inferior conjunctions) for Venus is 584 Earth days. An interesting, but unexplained, situation is that the rotation of Venus may be exactly locked to Earth. At each inferior conjunction, Venus presents the same face to Earth, despite the fact that the Sun's tidal pull on Venus exceeds the Earth pull by four orders of magnitude. Being closer to the Sun (0.72 AU), Venus receives nearly twice as much solar energy as the Earth. However, the Venus albedo (0.71) is nearly twice that of Earth (0.39), so that the effective radiation temperature of Venus (244° K) is, in fact, lower than that of Earth (253° K). Three other major differences between Venus and Earth are the high surface temperature at Venus (750° K compared to 300° K on Earth), the high atmospheric surface pressure (100 times that of Earth), and the extreme aridity at Venus (water abundance 10^{-4} that on Earth). Finally, Earth possesses a strong magnetic field (about 0.5 gauss at the surface), whereas Venus probably has no intrinsic field (the upper limit on dipole moment is 3×10^{-4} of the Earth's).

The most ancient observations of the planet on record come from Babylonia, as recorded on the famous Venus Tablet (ref. 1). Basic information concerning Venus began to be accumulated following the invention of the telescope, when, in 1610, Galileo first studied the phases of Venus. A major finding of the telescope was that Venus is entirely shrouded in clouds, making it impossible to see the surface in the visible, which explains the high albedo. The fact that Venus has an atmosphere was discovered by the Russian astronomer, M. V. Lomonsov, in 1761, studying a blurred transit of Venus across the solar disc (ref. 4). The 1930's witnessed the application of infrared spectroscopy to astronomy, and the first indication of a mainly carbon dioxide atmosphere at Venus was suggested (ref. 3). The birth of radio astronomy and radar astronomy in the mid-1950's permitted us to "see" below the clouds of Venus down to the surface. Thus the picture evolved that the lower atmosphere of Venus was hot and dense, and that the surface was topographically smooth compared to Earth. Beginning in 1962, the first spacecraft was sent to Venus, inaugurating a new age in planetary exploration. The last decade has seen greater progress in understanding Venus than the previous 350 years of telescopic astronomy. To dramatize our lack of knowledge before the space age, consider a survey of Venus (ref. 6) concerning the available facts and theories in 1961:

Facts:
(1) Atmosphere CO_2-rich.
(2) Planet emitted substantial radio wavelength flux.

Theories:
(1) Moist, swampy, teeming with life, or
(2) Warm, enveloped by global carbonic acid ocean, or
(3) Cool, Earth-like, surface water, dense ionosphere, or
(4) Warm, massive precipitating clouds of water droplets, intense lightning, or

(5) Cold polar regions with 10-km-thick icecaps, hot equatorial region far above H_2O boiling point, or
(6) Hot, dusty, dry, windy, global desert, or
(7) Extremely hot, cloudy, molten lead and zinc puddles at equator, seas of bromine, butyric acid, phenol at poles.

It is not obvious that scientists were even talking about the same planet in 1961!

1.2.2 Venus science objectives - Following the first missions to Venus, a relatively large number of studies addressed themselves to Venus exploration science objectives (refs. 7 and 8). Goody suggested 24 specific objectives based on the solar-system objectives outlined above (ref. 9). These first-order questions (table III) were used to evaluate the scientific potential of the Pioneer Venus program. Recently, Lewis and Friedman (ref. 10) took a fresh look at the problem and identified seven major areas of ignorance regarding Venus (table IV). For the purposes of this study, we have divided the Venus environment into five regions (ionosphere, atmosphere, clouds, surface, and interior) and, with the aid of the above-referenced material, we have constructed a composite list of Venus Exploration Science Objectives (table V). This last list was used as a starting point to our study.

A few words are in order here regarding Venus as a potential contributor to comparative planetology and comparative meteorology. More detail is provided in subsequent sections. Visual mapping of the surfaces of Earth, Mars, Mercury, and the Moon has determined some very interesting similarities and differences. Venus, because of its ubiquitous cloud cover, can be mapped only by radar. As the last of the terrestrial planets, with its dense atmospheric blanket, Venus is a critical contributor to the comparative planetology studies. The value of Venus exploration for comparative meteorology and climatology has been emphasized in many previous studies. In fact, it was the prime argument used to justify Pioneer Venus as a new start in FY 75 (ref. 11). The arguments can probably be understood best by isolating one particular aspect - planetary circulation. Many complex and interacting factors serve to establish planetary-scale atmospheric circulation (refs. 6 and 12) on any planet (table VI). Each of the terrestrial planets, Earth, Venus, and Mars, offers quite unique situations for many of these factors (table VII). Each of the quite different "laboratories" can provide data to test general meteorological and climatological theories.

1.3 Missions to Venus

1.3.1 Previous missions - Since 1962, there have been eight missions to Venus: three U. S. missions, all "flybys," and five U. S. S. R. missions, all buses (upper atmospheric measurements) and single entry probes (atmosphere and surface measurements). The launch/encounter characteristics for these missions are summarized in table VIII for Mariners 2, 5, and 10 and Veneras 4-8. The encounter dates versus solar sunspot number are shown in figure 2. Launch opportunities occur near each inferior conjunction, separated by one synodic period, that is, 584 days or about 19 months. Note that since 1967, either

TABLE III.- VENUS EXPLORATION SCIENCE OBJECTIVES (1)

First-Order Questions About Venus (Pioneer Venus 1972)

(1) CLOUD LAYERS - Number, location, variation over planet?
(2) CLOUD FORMS - Stratiform, cumuliform, haze?
(3) CLOUD PHYSICS - Opacity, particle sizes, number densities?
(4) CLOUD COMPOSITION - Chemical composition of different layers?
(5) SOLAR HEATING - Solar radiation depositories?
(6) DEEP CIRCULATION - Wind in lowest 3-4 scale heights?
(7) DEEP DRIVING FORCES - Low-altitude horizontal temperature gradients?
(8) DRIVE FOR FOUR-DAY WIND - Horizontal temperature gradients (10-100 MB)?
(9) LOSS OF WATER - Has water been lost and how?
(10) CO_2 STABILITY - Why its upper atmosphere stability?
(11) SURFACE COMPOSITION - Crustal composition?
(12) SEISMIC ACTIVITY - Level?
(13) EARTH TIDES - Do they exist, amplitude?
(14) GRAVITATIONAL MOMENTS - Figure, higher moments?
(15) EXTENT OF FOUR-DAY WIND - Vertical and latitudinal distributions?
(16) VERTICAL TEMPERATURE STRUCTURE - Isothermal region? Departures from adiabaticity? Structure near cloud top?
(17) IONOSPHERIC MOTIONS - Transport, night-time ionization
(18) TURBULENCE - Intensity in deep atmosphere
(19) ION CHEMISTRY - Species and reactions?
(20) EXOSPHERIC TEMPERATURE - Variations over planet?
(21) TOPOGRAPHY - Features, relations to thermal maps
(22) MAGNETIC MOMENT - Internal field?
(23) BULK ATMOSPHERIC COMPOSITION - Major gases to 1-percent level?
(24) ANEMOPAUSE - Solar-wind interaction processes?

TABLE IV.- VENUS EXPLORATION SCIENCE OBJECTIVES (2)

Major Areas of Ignorance (After Lewis and Friedman, ref. 10)

(1) Overall elemental composition and internal structure of the planet can only be surmised.
(2) Crustal composition and age and internal structure required to model thermal and differentiation history of planet.
(3) Almost no evidence regarding crustal tectonic processes, presence or absence of true continental blocks, continental drift, or volcanism.
(4) No compositional information to permit unraveling the provenance and history of volatiles and processes that dominate atmospheric evolution.
(5) Observational knowledge of atmospheric circulation limited to cloud-top, medium resolution UV imaging and incomplete pressure, temperature, density, opacity, and Doppler tracking data.
(6) Mapping of gravitational field scarcely begun.
(7) Mapping of surface by Earth-based radar far short of quality necessary to interpret regional and local geologic structure and history.

TABLE V.- VENUS EXPLORATION SCIENCE OBJECTIVES (3)

Ionosphere

- STRUCTURE - Electron and ion density distributions
- COMPOSITION - Ions
- CHEMISTRY AND PHOTOCHEMISTRY - Electrons and ions
- ENERGY BALANCE - Neutral, ion, electron temperatures
- DYNAMICS - Ion and electron flow, maintenance of night-time ionosphere, escape
- SOLAR-WIND INTERACTION - Ionopause, scavenging, charge exchange, heating

Atmosphere

- STRUCTURE - Pressure, temperature, density, energy balance
- COMPOSITION - Major and rare gases, cloud-forming condensates, aerosols, loss of H_2O, hydrogen escape, solar gas capture
- CHEMISTRY AND PHOTOCHEMISTRY - Neutral gas reactions, CO_2 stability
- DYNAMICS - Deep circulation, driving forces, four-day wind, turbulence, eddy diffusion, and mixing
- SOLAR HEATING - Molecular opacity, sources and sinks, deposition

Clouds

- STRUCTURE - Number of layers, locations vertically and horizontally, forms: Stratiform, cumuliform, haze
- COMPOSITION - Condensibles, aerosols
- FORMATION - Physics of, UV markings
- OPACITY - Densities, particle size

Surface

- TOPOGRAPHY - Shape, form, meteoritic cratering, mountains
- PLANETOLOGY - Geologic structure and history, dynamic processes, isostatic compensation
- COMPOSITION AND MINERALOGY
- ALBEDO
- SEISMIC ACTIVITY
- SOLID-BODY TIDES
- VOLCANISM

Interior

- STRUCTURE - Differentiation, mass distribution
- COMPOSITION - Elemental, crustal
- THERMAL STRUCTURE AND HISTORY
- GRAVITATIONAL MOMENTS - Figure
- MASS AND RADIUS
- MAGNETIC MOMENT
- CRUSTAL TECTONICS, CONTINENTAL BLOCKS, AND DRIFT
- PLANETARY RETROGRADE ROTATION

TABLE VI.- FACTORS IN PLANETARY-SCALE ATMOSPHERIC CIRCULATION

(After Lewis, ref. 6)

(1) Penetration of sunlight into atmosphere
(2) Absorption of sunlight at surface; re-emission of IR radiation
(3) Absorption of IR radiation by atmosphere
(4) Convection of heated atmospheric parcels
(5) Radiative cooling on night side and high latitudes
(6) Mass atmospheric motion conveying heat from equator to poles or from subsolar to antisolar regions
(7) Flow distortion due to Coriolis effects
(8) Evaporation, condensation, transport of latent heat
(9) Modification of radiative processes by cloud cover
(10) Steering of winds by topography
(11) Local meteorological effects

TABLE VII.- COMPARATIVE CONDITIONS FOR METEOROLOGY

Factors	Earth	Venus	Mars
Surface atmospheric pressure	1 atm	100 atm	0.01 atm
Surface temperature	310° K	770° K	210° K
Nature of surface	Liquid & solid	Solid	Solid
Surface topography	≤8 km (S.L.)	≤6 km	≤25 km
Planetary rotation, Earth days	1	243	1.026
Seasons	Yes	No	Yes
Cloud coverage	~50 percent	100 percent	Rare
Major transport process	Mixed	Convection	Radiation
Composition	N_2, O_2	CO_2	CO_2

TABLE VIII.- SPACECRAFT MISSIONS TO VENUS

Spacecraft	Launch	Encounter	Type	Encounter characteristics	Reference
Mariner 2	Aug. 27, 1962	Dec. 14, 1962	Flyby	Closest approach: 34833 km	13
Venera 4	Jun. 12, 1967	Oct. 18, 1967	Bus and entry probe	Entry to destruction Lower atmosphere, hard lander, nightside	14
Mariner 5	Jun. 14, 1967	Oct. 19, 1967	Flyby	Closest approach: 4100 km	15
Venera 5	Jan. 5, 1969	May 16, 1969	Bus and entry probe	Entry to destruction Lower atmosphere, hard lander, nightside	16
Venera 6	Jan. 10, 1969	May 17, 1969	Bus and entry probe	Entry to destruction Lower atmosphere, hard lander, nightside	16
Venera 7	Aug. 17, 1970	Dec. 15, 1970	Bus and entry probe	Entry to destruction Lower atmosphere, hard lander, nightside	16
Venera 8	Mar. 27, 1972	Jul. 22, 1972	Bus and entry probe	Entry to destruction Lower atmosphere, hard lander, dayside	17
Mariner 10	Nov. 2, 1973	Feb. 5, 1974	Flyby	Closest approach: 5785 km	18
Pioneer Venus	May 1978	Dec. 1978	Orbiter	Periapsis: 150 km; apoapsis: 66000 km; period: 24 hr; incl: 105° retrograde	19
Pioneer Venus	Aug. 1978	Dec. 1978	Bus and entry probe	Entry to destruction Lower atmosphere, 4 hard landers, night/day	20

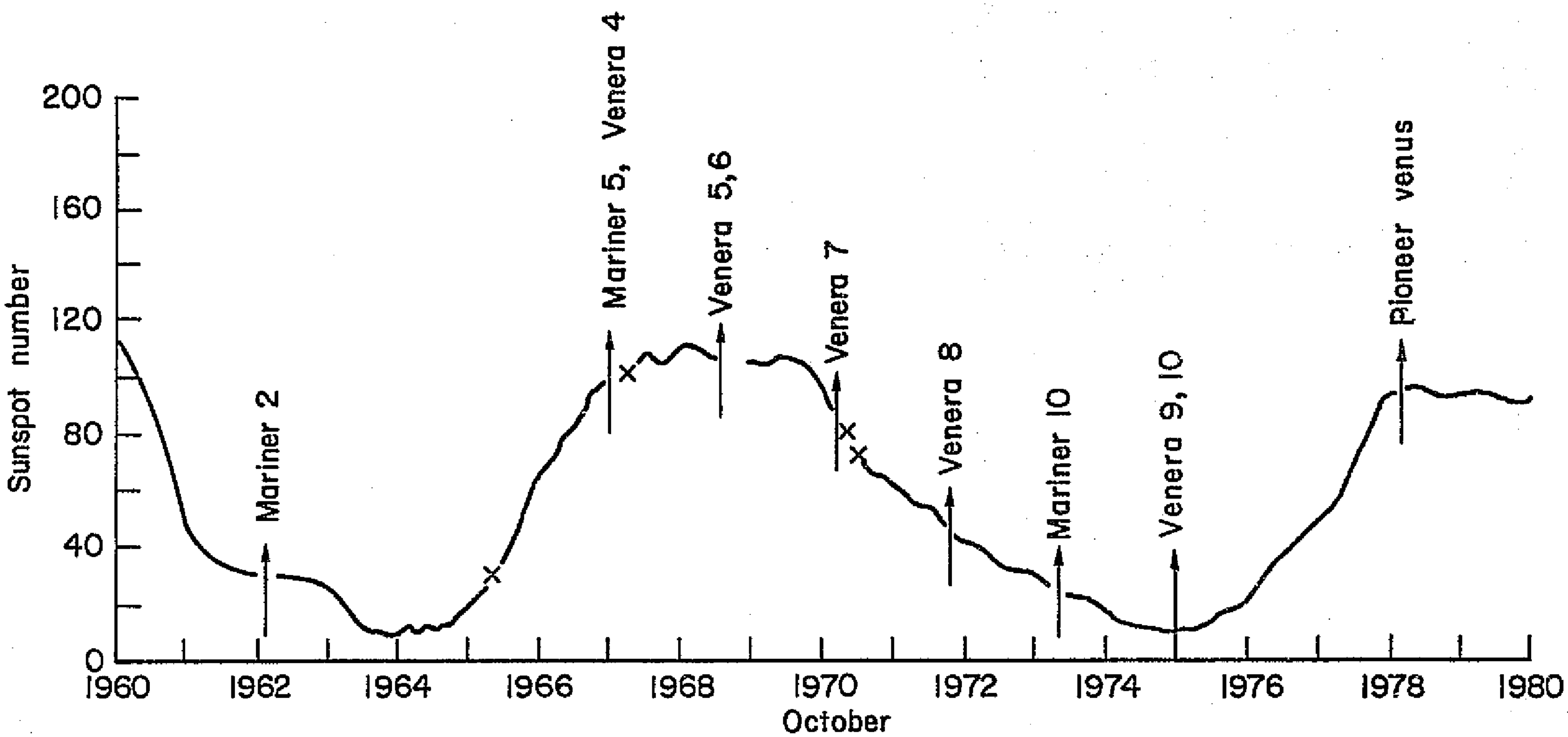


Figure 2.- Venus missions and the solar sunspot cycle.

the U. S. or U. S. S. R. or both have taken advantage of each of the five launch opportunities through 1974. The location of the Venera 4-8 entry sites and the Mariner 5 and 10 radio-occultation tangents (ref. 21) are shown in figure 3. All Venera entries were at low latitudes (<20°) and on the nightside of the planet near the morning terminator, except for Venera 8 which was on the dayside near the terminator. The scientific payloads of the Mariner spacecraft are shown in table IX.

1.3.2 Pioneer Venus - The Pioneer Venus program, consisting of two launches (table VIII), will provide the first orbiter mission and the first bus/multiple entry probe mission to Venus (refs. 9, 19, and 20). The missions are described in appendix A; for comparison, the scientific payloads are given in tables X through XII. Figure 4 shows the Venus measurement regimes (ionosphere, atmosphere, clouds, surface, interior) in which the various experiments will make measurements. The currently planned impact locations of the bus, large probe, and small probes are shown in figure 5. The suborbital track of the orbiter is also shown. These latter two figures clearly indicate the improvements in planetary coverage afforded by Pioneer Venus compared with the Venera series. The Pioneer Venus Orbiter radio-occultation season will last for some 70 days of the 243-day mission. The entry and exit tangent points will be at high northern and southern latitudes (because of the high orbit inclination) and mainly on the nightside for both cases. The scientific objectives of the Pioneer Venus orbiter and multiprobe missions are given in tables XIII and XIV, respectively (refs. 9 and 22).

1.3.3 Future Venus missions - Although the United States will not launch a mission to Venus until the 1978 opportunity (Pioneer Venus), thus skipping the 1975 and 1977 opportunities, it is expected that the U. S. S. R. will take advantage of them. The only Venus mission currently planned by the U. S. beyond Pioneer Venus is the surface mapping mission VOIR (Venus Orbiter Imaging Radar) planned for a dual launch in the 1983 opportunity (ref. 23; personal communication, R. S. Kraemer). There is a suggestion of a joint U. S. S. R./French balloon mission in 1981 or 1983 (J. Blamont and T. M. Donahue, personal communications).

The present study was undertaken to recommend future missions to Venus in the post-Pioneer Venus time frame, that is, beyond 1980. Earlier studies (refs. 7 and 9) recommended that the United States undertake a series of low-cost (i.e., Explorer or Pioneer class) Venus missions at each launch opportunity. The Pioneer Venus missions are the first in that series. Whether or not VOIR is the most logical follow-on, or whether another mission(s) is more desirable is a subject with which we shall deal.

1.4 Outline of Report

Section 2.0 summarizes the conclusions and recommendations of the study. Section 3.0 surveys what we know today (1975) concerning Venus and the major scientific questions surrounding that planet. In section 4.0, we attempt to forecast what we will learn from ground-based spectroscopic and radar mapping studies of the planet from 1975-1979 and what we will learn from the Pioneer Venus missions (1978-1979). Section 5.0 attempts to summarize the unknowns

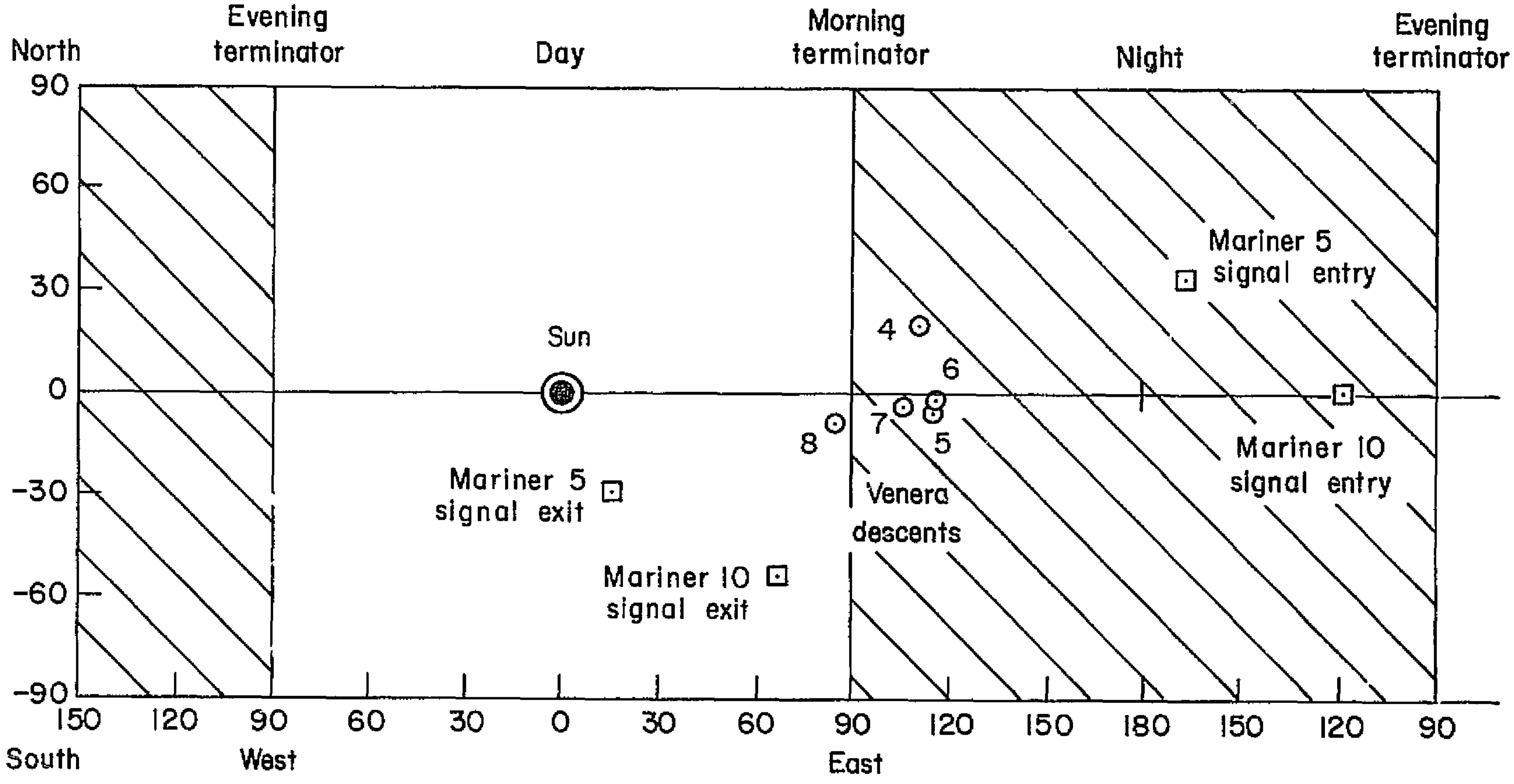


Figure 3.- Venera impact locations and Mariner occultation geometry.

TABLE IX.- PRE-PIONEER VENUS EXPLORATION

	Participant
MARINER 2 (1962)	
Microwave radiometer	Barrett/MIT
Infrared radiometer	Kaplan/JPL
Magnetometer	Coleman/UCLA
Charged-particle detectors	Van Allen/Iowa - Anderson/JPL
Cosmic dust	Alexander/GSFC
Solar plasma probe	Neugebauer/JPL
MARINER 5 (1967)	
Magnetometer	Smith/JPL
Solar plasma probe	Bridge/MIT
Charged-particles detector	Van Allen/Iowa
S-Band occultation	Kliore/JPL
Dual-frequency occultation	Eshelman/Stanford
UV photometer	Barth/Colorado
Celestial mechanics	Anderson/JPL
MARINER 10 (1974)	
Celestial mechanics	Howard/Stanford
S/X radio-occultation	Howard/Stanford
Charged particles	Simpson/Chicago
EUV spectrometer	Broadfoot/KPNO
Infrared radiometer	Chase/SBRC
Magnetometer	Ness/GSFC
Solar plasma probe	Bridge/MIT
TV science	Murray/CIT

TABLE X.- PIONEER VENUS SCIENTIFIC PAYLOAD ORBITER MISSION

Experiment	Participant
Neutral mass spectrometer (ONMS)	H. Neimann/GSFC
Ion mass spectrometer (OIMS)	H. Taylor/GSFC
Retarding potential analyzer (ORPA)	W. Knudsen/LMSC
Electron temperature probe (OETP)	L. Brace/GSFC
Ultraviolet spectrometer (OUVS)	A. Stewart/Colorado
Plasma wind analyzer (OPA)	J. Wolfe/ARC
Magnetometer (OMAG)	C. Russell/UCLA
Infrared radiometer (OIR)	F. Taylor/JPL
Imager/photo-polarimeter (OCPP)	J. Hansen/GISS
Radar altimeter (ORAD)	Team*
Electric field detector (OEFD)	F. Scarf/TRW
Gamma ray burst detector (OGBD)	W. Evans/LASL

*Radar Altimeter Team Members: G. Pettengill/MIT - Leader, D. Staelin/MIT, W. Kaula/UCLA, W. Brown/JPL, H. Masursky, USGS, and G. McGill/Univ. Mass.

TABLE XI.- PIONEER VENUS SCIENTIFIC PAYLOAD MULTIPROBE MISSION

	Participant
LARGE PROBE	
Neutral mass spectrometer (LNMS)	J. Hoffman/UTD
Gas chromatograph (LGC)	V. Oyama/ARC
Atmosphere structure (LAS)	A. Seiff/ARC
Solar radiometer (LSFR)	M. Tomasko/Arizona
Infrared radiometer (LIR)	R. Boese/ARC
Cloud particle size spectrometer (LCPS)	R. Knollenberg/PMS
Nephelometer (LN)	B. Ragent/ARC, J. Blamont/CNES
SMALL PROBE	
Atmosphere structure (SAS)	A. Seiff/ARC
Nephelometer (SN)	B. Ragent/ARC; J. Blamont/CNES
Net flux radiometer (SNFR)	V. Suomi/Wisconsin
BUS	
Neutral mass spectrometer (BNMS)	U. Von Zahn/Bonn
Ion mass spectrometer (BIMS)	H. Taylor/GSFC
RADIO EXPERIMENT	
DVLBI	G. Pettengill/MIT

TABLE XII.- PIONEER VENUS RADIO SCIENCE TEAM EXPERIMENTS

SCIENCE OBJECTIVES

(1) Ionosphere electron density profiles - Kliore, Croft (2)*
(2) Thermosphere density and scale height - Keating, Shapiro (1)
(3) Lower atmosphere pressure, temperature, density profiles - Kliore, Croft (2)
(4) Cloud layering - Kliore, Croft (2, 3)
(5) Atmospheric turbulence - Woo, Croft (2)
(6) Cartography and geology - Masursky, McGill (1, 4)
(7) Internal density distribution, isostatic compensation - Phillips, Shapiro (1, 4)
(8) Venus mass, gravity harmonics, spin vector, orbit inertial reference, polar motion, mascons, convection - Shapiro (1, 4)
(9) Solar corona density fluctuations - Woo, Croft (2, 3)
(10) Solar wind perturbations - Croft (3)
(11) General relativity - Shapiro (2, 5)
(12) Precession and nutation constants - Shapiro (2, 5, 6)

TECHNIQUES

(1) Doppler tracking - S, S&K-bands
(2) Radio-occultation - S&X-bands, Venus and solar (OOCC)
(3) S&X-band differential dispersion and absorption
(4) Radar altimetry - orbiter and Earth-based
(5) Ranging transponder
(6) VLBI-orbiter and galactic sources

*Refers to techniques listed above.

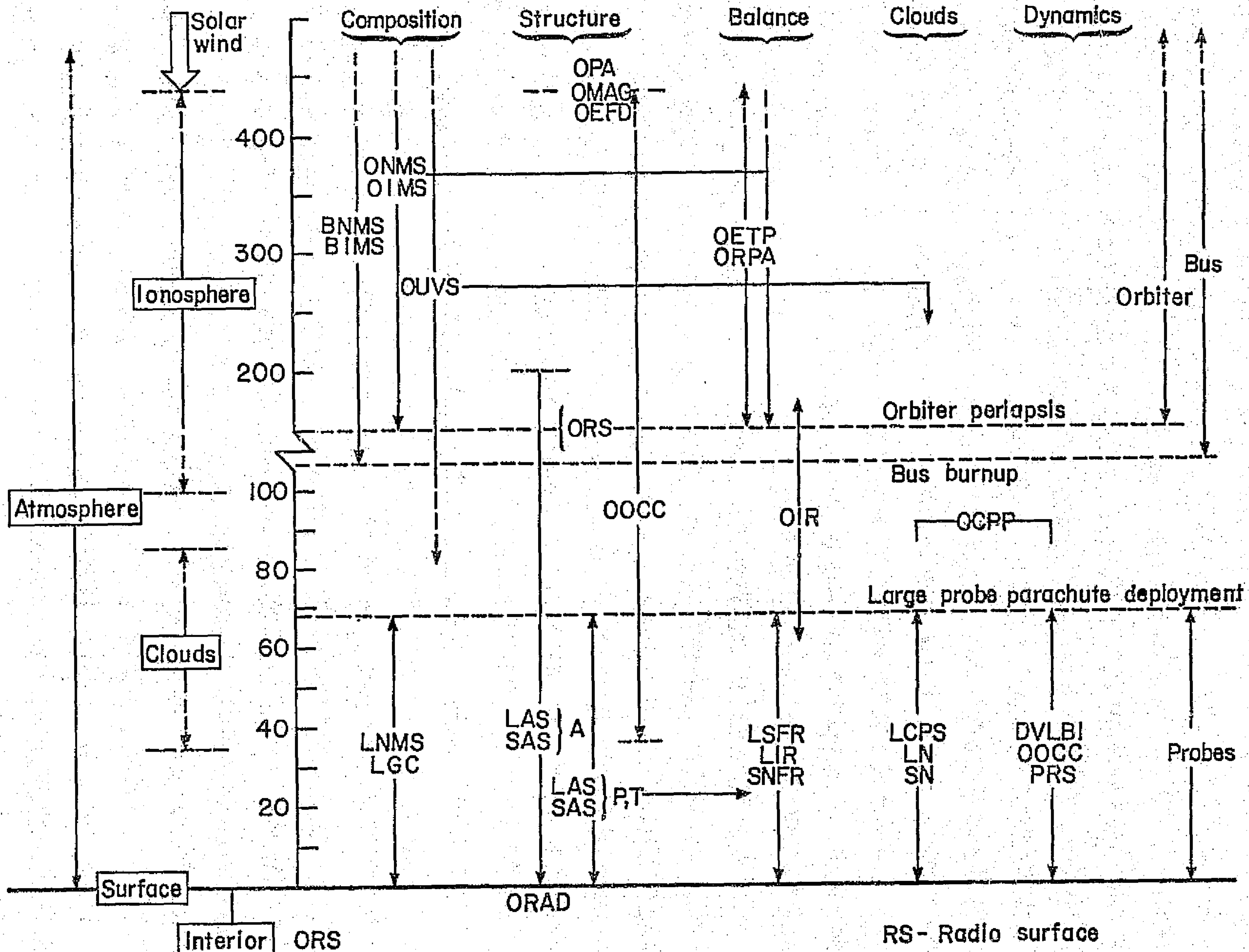
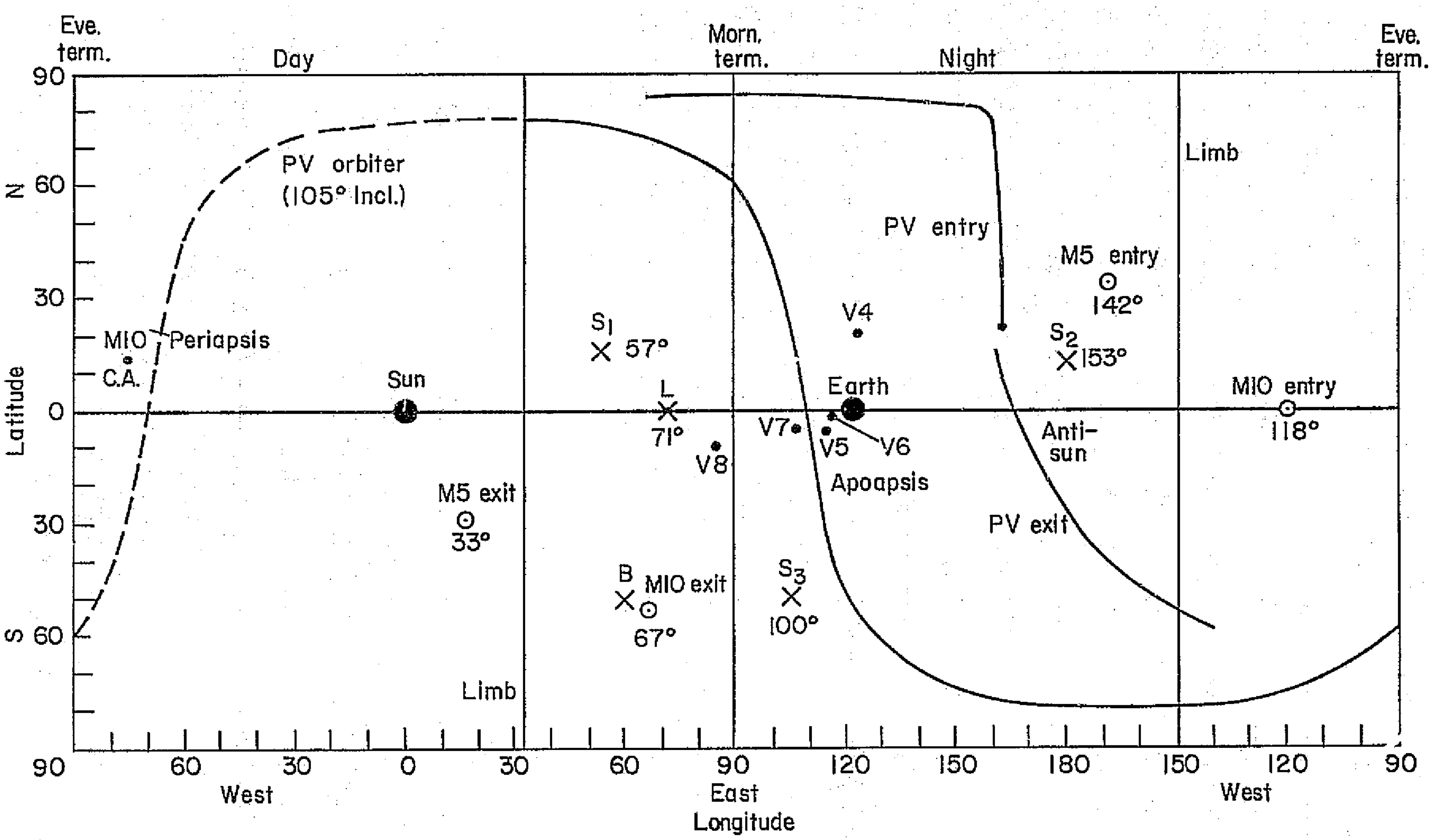


Figure 4.- Pioneer Venus experiment coverage.



● Sub – Solar, sub – earth points

× Pioneer venus multiprobe entry points (Solar zenith angle indicated)

⊙ Mariner 5, 10 occultation tangent points (Solar zenith angle indicated)

MIO C.A. – sub-satellite point of MIO at closest approach

• V4-8 – Venera 4-8 entry points

PV entry, exit lines – range of occultation tangent points over 80 day season

Figure 5.- Pioneer Venus impact locations and occultation geometry.

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TABLE XIII.- PIONEER VENUS SCIENTIFIC OBJECTIVES - ORBITER MISSION

(1) Global mapping of the atmosphere and ionosphere by remote sensing and radio occultation to extend the information obtained on the vertical structure from the entry probe mission.
(2) Global studies by in-situ measurements of the upper atmosphere, ionosphere, and solar-wind/ionosphere interaction region to extend and supplement the information obtained with the entry probe mission.
(3) Studies of the planetary surface by remote sensing.
(4) Determination of gravitational field harmonics from perturbations of the spacecraft orbit.

TABLE XIV.- PIONEER VENUS SCIENTIFIC OBJECTIVES - MULTIPROBE MISSION

(1) Bulk, trace, and isotopic composition of atmosphere
(2) Comparative structure of the atmosphere at four entry sites
(3) Vertical location and characterization of clouds
(4) Solar and planetary radiative flux deposition
(5) General circulation pattern of the atmosphere
(6) Nature of the solar-wind/atmosphere interface

about Venus remaining at the end of the decade and upon which our recommendations for the 1980's are based. Sections 6.0, 7.0, 8.0, and 9.0 deal with the capabilities and constraints associated with orbiters, probes, balloons, and landers, respectively, as scientific payload carriers. Each of these vehicles has unique capabilities with regard to in situ versus remote sampling, local coverage versus global coverage, and applicability to the environment regimes, that is, ionosphere, atmosphere, clouds, surface, and interior. Each of sections 6.0 through 9.0 deals with one of the vehicle types available for planetary exploration. The appendices present various important facts and auxiliary studies related to the major study.

2.0 SUMMARY OF MAJOR CONCLUSIONS AND RECOMMENDATIONS

We present here only the major conclusions and recommendations resulting from the current study. Each conclusion and recommendation is annotated with specific sections of the report to which the reader is referred for in-depth discussion.

2.1 Major Conclusions

(1) The role and importance of continuing exploration of Venus in helping to fulfill solar-system planetary exploration objectives is clear and unquestioned. Venus is of equivalent importance to Earth, Mars, and Jupiter for comparative meteorology and climatology studies, and to Earth, Mars, Mercury, the Moon, and other planetary satellites for comparative planetology studies (section 1.0).

(2) Considering all the major scientific questions associated with planetary exploration (section 1.0), probably fewer are answered for Venus currently than for any other terrestrial planet (Mercury, Moon, Earth, or Mars). This ignorance is, of course, not due to lack of intrinsic interest, but rather due to the difficulties of remotely sensing the planetary surface and the atmosphere below the ubiquitous cloud cover (section 3.0).

(3) Despite the apparent proliferation of interest in Venus exploration during the next few years, many first-order questions will remain unanswered (section 5.0) and Venus will probably remain the least understood of the terrestrial planets at the end of the decade. The Pioneer Venus program, consisting of a single orbiter mission and multiple entry probe mission, both to be launched during the 1978 opportunity (appendix A), will address (section 4.0) many of the outstanding scientific questions concerning Venus (section 1.0) during the encounter lifetime (Dec. 1978-Aug. 1979). In addition, Earth-based radar observations of the planet's surface in the period 1975-1980 with much improved spatial resolution and sensitivity will provide valuable geologic data (section 6.0). Although the 1975 and 1977 launch opportunities will be passed up by the United States, significant surface and atmospheric data may well be provided by Venera series missions expected to be launched[1] by the U. S. S. R. during these periods and during the 1978 opportunity. These accomplishments will greatly increase our knowledge of Venus; however, existing and new knowledge relating to the other terrestrial planets will serve to maintain their current advantage. Mercury is relatively uninteresting meteorologically, and its surface characteristics were explored with the three recent Mariner 10 imaging flybys, at least for half the planet. Mars is of vital interest to both comparative meteorology and planetology, but with the completion of the Mariner 9 orbiter mission in 1972 and the Viking mission in 1976, giant steps toward understanding the red planet will have been taken.

(4) Clearly, follow-on missions to Venus should be given high priority, and a reasonable fraction of the NASA planetary program "planning wedge" dollars should be devoted to them. Scientifically attractive and cost-effective missions to Venus are conceptually available and can be implemented with achievable spacecraft and launch vehicle technology for launch in the early 1980's (sections 6.0 to 9.0, appendix B). Orbiters (section 6.0) and landers (section 9.0) are particularly attractive for addressing questions associated with the planetary surface and interior, while questions on the atmosphere unanswered by Pioneer Venus are best investigated by advanced entry probes (section 7.0), balloons (section 8.0), and orbiters (section 6.0). Within each spacecraft type, there is a broad spectrum of mission possibilities ranging from single, simple, small, short-lived to multiple, relatively advanced, large, long-lived vehicles.

(5) The study results suggest a reasonable and justifiable mission strategy for post-Pioneer Venus exploration (section 2.2). Realistically, however, any scenario must be reassessed critically following major advances

[1]At the time of this writing, Veneras 9 and 10 have been launched and are scheduled to encounter Venus in October 1975. Information relating to the scientific objectives and payloads has not yet been released.

to current scientific knowledge. Certainly, major reevaluation points will coincide with the completion of Venera missions during the 1975, 1977, and 1978 opportunities, and with the Pioneer Venus missions in 1978-1979.

(6) A lasting major value resulting from this study and from the development of a mission strategy extending over 1-1/2 decades is the early identification of critical areas requiring technology development. Long lead-time developments must be initiated before the 1980's, particularly for lander, entry probe, and balloon missions, if available hardware is to keep pace with the recommended missions (section 2.3).

2.2 Major Recommendations

Although we recognize the important role that limited funding will play in the final planning and selection of future missions, we have attempted to separate scientific considerations from economic ones. Our recommendations are based mainly on the former and on appraisals of available and foreseeable technology. However, they have also been evaluated for fiscal realism against the space sciences planetary program budgetary expectations.

Since timing is a critical aspect of planetary exploration planning, it is instructive to address the question of desirable mission frequency. Venus launch opportunities occur at roughly 19-month intervals. In view of the large number of identified missions of high scientific value, it is our recommendation that missions be planned to coincide with every second Venus opportunity. To launch a mission at every opportunity is not efficient from the viewpoint of information returned in relation to effort expended, primarily because a 19-month spacing does not permit findings and questions from one mission to be properly evaluated and factored into the next mission. On the other hand, missions at every third opportunity (i.e., 57 months) are so widely spaced that progress in exploration would be tantalizingly slow. It would be difficult to sustain a continuously productive effort, not to mention widespread scientific interest and support, particularly in light of a U. S. S. R. program that apparently will take advantage of almost every opportunity. Most importantly, the acquisition of comparative meteorology data, which could have very real and important implications with respect to understanding the weather here on Earth and its long-term trends and variations, a problem of great potential economic and human value, would be unduly delayed.

The recommended sequence of Venus exploration missions is shown in table XV. Four missions, including Pioneer Venus, are recommended for the seven launch opportunities between May/August 1978 and March 1988. An orbiter mission dedicated primarily (but not exclusively) to global, high-resolution surface mapping is recommended for the 1981 opportunity as a follow-on to the atmospherically oriented Pioneer Venus 1978 mission. A multiple lander mission dedicated primarily to regional surface measurements is recommended for the 1985 opportunity. Finally, an atmospherically oriented mission is recommended for the 1988 opportunity.

There is little question that the least known scientific aspects concerning Venus in the post-Pioneer Venus era will involve surface (certainly on a

TABLE XV.- RECOMMENDED SCENARIO

Launch date	May/Aug. 1978	March 1980	November 1981	June 1983	January 1985	August 1986	March 1988	November 1989	June 1991
Basic mission	Pioneer Venus Orbiter/ Multiprobe		Venus Orbiter Imaging Radar (VOIR)		Multiple-Surface Lander		Atmos-pheric		?
New start year (start date)	FY-75 (Dec. 1974)	FY-76 (Mar. 1976)	FY-78 (Nov. 1977)	FY-79 (June 1979)	FY-81 (Jan. 1981)	FY-82 (Aug. 1982)	FY-84 (Mar. 1984)	FY-86 (Nov. 1985)	FY-87 (June 1987)
Basic mission cost ROM FY-75 M$	169		205		200-400		175		

TABLE XVI.- PROPOSED VENUS EXPLORATION VERSUS PLANNING WEDGE ($M)

	75	76[a]	77	78	79	80	81	82	83	84	85	86	87	Total
Pioneer Venus (78)	20	71	39	19	12	9								169
VOIR (81)				26	86	77	16							205
Lander (85)							44	132	88	36				300
Atmosphere (88)										25	75	50	25	175
Total	20	71	39	45	98	86	60	132	88	61	75	50	25	
Planning wedge		4	114	248	396	400	490	580	666	666	666	666	666	
Percent	(b)	(b)	(b)	10[b]	22[b]	19[b]	12	23	13	9	11	8	4	

[a]Includes FY-7T (Includes three-month fiscal year redefinition).

[b]Pioneer Venus not included in planning wedge.

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global scale) and interior processes and properties (section 5.0). The best two-pronged approach to these problems appears to be an orbiter radar-imaging mission (section 6.0) followed by a survivable lander mission (section 9.0). Hence we recommend an orbiter radar-imaging mission to Venus as soon as possible following Pioneer Venus. The VOIR program, currently scheduled for the 1983 opportunity in the latest NASA mission model, appears to offer the maximum scientific return at the earliest possible date. Thus, we endorse the VOIR mission for the 1981 opportunity. Note that to accomplish this mission in 1981 requires an FY 77 or FY 78 new start at the latest. It is recognized that the VOIR mission faces significant competition as a new start, especially in light of a relatively small planning wedge, in those years (see table XVI). Thus the likelihood of a slip to the 1983 opportunity is high, to a point where a new start in FY 79 is more tolerable with respect to the planning wedge. If such a slip is deemed likely, we then recommend that radar imaging from a spin-stabilized spacecraft be fully assessed for scientific equivalence to and possible cost-advantage relative to the three-axis-stabilized VOIR (section 6.0).

An important aspect of the proposed orbiting radar mapper mission is that its desirability as a post-Pioneer Venus follow-on should remain unchallenged by Pioneer Venus, likely Venera missions, and ground-based observations. The Pioneer Venus radar altimeter will provide measurements of surface height to an accuracy of about 50 m with a 300-m resolution of surface variations. A limited number of image patches with 20 to 40 km square resolution elements may also be obtained. The U. S. S. R. program appears dedicated to atmospheric and spatially limited regional surface measurements. Ground-based radar observations of Venus will achieve, at best, 1-2-km resolution maps over perhaps 20-25 percent of the planet, at least up to 1980. Thus the scientifically justifiable requirement for ≤1-km resolution over 90-95 percent of the planet and ≤100-m resolution over at least 10 percent of the planet is achievable only from an orbiting radar mission (section 6.0).

The inclusion of one or more of the following nonradar experiment options (section 6.0) would greatly enhance the scientific effectiveness (hence the degree and extent of scientific community support) of the orbiter mission:

(a) Solar-wind interaction region measurements

(b) *In situ* aeronomy and ionospheric measurements

(c) Improved Pioneer Venus-type remote sensing measurements - high-resolution, short-term (~10 min) UV cloud imaging; IR spectrometry; short-wavelength (300-1100 Å) ultraviolet spectrometry; multiwavelength microwave radiometry

(d) Improved gravity field measurements, possibly by means of a small subsatellite

Another desirable, though more complex, option would include deployment of a very simple balloon experiment providing "ground-truth" observations for the remote sensing observations of winds above the cloud tops and as a precursor to a more extensive balloon mission (1988?).

As shown in table XV, any mission to be launched during the 1985 opportunity requires a new start in FY-81 (at least by Jan. 1981). By this time, the results from the Pioneer Venus program and from the Venera programs in 1975, 1977, and 1978 should be fully available as well as results from the continuing ground-based programs. A major decision will need to be made at that point whether to continue Venus exploration in 1985 with a lander mission or an atmospherically oriented mission. The best current strategy appears to be to postpone detailed consideration (but not required SRT developments) of an atmospherically oriented mission until the results of Pioneer Venus are known. On the other hand, the design of a lander mission does not depend significantly on Pioneer Venus results, although the likely Venera program impacts may be substantial. Nevertheless, in view of the high return of atmospheric data expected from Pioneer Venus, we recommend a multiple-lander mission for the 1985 opportunity (section 9.0). The spectrum of options potentially available within this category is indeed broad, ranging from a large number of very small, short-lifetime (~1 hr) devices deployed from an orbiter, or perhaps from balloons, or as integral parts of atmospheric entry probes, to a fewer number of larger, medium-lifetime (~10-20 hr) landers widely deployed from orbit. Even longer-lived landers (~days) are not beyond the realm of feasibility for the 1985 time period. The primary objective of short-lived landers would be rudimentary geochemical composition measurements while the medium-lived landers would incorporate seismic observations, more sophisticated geochemistry, and perhaps magnetometry.

Any recommendation for a lander mission to Venus must incorporate in its rationale sufficient consideration of the extent of U. S. S. R. competition, a program that clearly has landed science as its main current and probably future thrust. This is not a simple task and it will not become easier as time passes. The United States has the apparent advantage of being able to produce much more sophisticated scientific experiments. This current advantage must be maintained and exploited. Venus is too important a scientific object to leave completely to others for exploration.

Finally, an obvious and desirable nonsurface-oriented science option as an addition on the landers is to incorporate atmospheric experiments. In fact, we recommend that any lander mission to Venus incorporate as much atmospheric science as possible without compromising the surface science and, conversely, that any atmospheric mission incorporate as much surface science as possible without compromising the atmospheric science.

The atmospherically oriented mission recommended for the 1988 opportunity must await Pioneer Venus results before well-justified objectives can be selected. We have investigated potential advanced entry probe and balloon missions based on questions not likely to be answered by Pioneer Venus (sections 7.0 and 8.0), but the shortcomings are not quantifiable presently. We believe the shortcomings will lie in three areas: (1) lack of truly global coverage, (2) lack of adequate definition of physical and chemical processes in the Venusian upper atmosphere, and (3) lack of sufficient definition of cloud properties.

The recommended entry probe mission is designed to respond to these needs and consists of a large probe and two small probes, the latter deployed from Venus orbit. The large probe would incorporate aerodynamic lift, resulting in

a zoom-climb maneuver to make possible in situ investigations between 80 and 170 km altitude. It would then reenter through the upper and lower atmospheres near the subsolar region which is inaccessible to Pioneer Venus. The small probes would likewise be targeted to high interest regions of the planet - one to a pole and one to the backside of the planet which Pioneer Venus cannot reach (section 7.0).

A range of balloon options has been studied (section 8.0). Several attractive possibilities are available (circulation measurements, cloud property measurements, "ground-truth" measurements for orbiter and Earth-based observations; atmospheric structure and/or surface property measurements by means of dropsondes). The value of these data to provide "ground-thruth" for Earth-based and orbiter observations would be very great. However, an infusion of SRT funds is required to make the desired highly capable balloon missions feasible and to improve many of the operating characteristics. Critical Venus environmental data are required before sophisticated balloon missions of maximum value can be designed in detail: further definition of circulation patterns, updraft intensity and frequency, acid content of clouds, and solar flux versus altitude. These data should be forthcoming from Pioneer Venus.

2.3 SRT Requirements

The development of technological requirements and experiments for the recommended missions requires long lead-times in some cases, but no insurmountable difficulties or obstacles are identified. As the exploration of Venus proceeds beyond Pioneer Venus, we must recognize the absolute requirements for new sophisticated technology and instrumentation; we cannot continue the "off-the-shelf" myth. Thus, we strongly urge that NASA revitalize its SRT program as soon as possible to provide funds for the necessary instrument and other technological developments well in advance of mission approval. Critical items for SRT developments are listed in table XVII.

2.4 Other Considerations

A broad spectrum of options within each of the mission categories recommended for the 1981, 1985, and 1988 opportunities was investigated in the course of this study (sections 6.0-9.0). Mission launch weights ranged from as little as 500 kg to as high as 4000 kg which require launch vehicles ranging from the Atlas/Centaur to the Shuttle/IUS. Final mission designs depend on the nation's launch vehicle scenario in the post-1980 time frame, that is, whether there is a mix of conventional launch vehicles and the space shuttle or whether only the shuttle will be available. Current estimates are that the latter situation will occur. All of the proposed missions can be launched by the shuttle plus an interim upper-stage (IUS) derivative. Table XVIII lists the launch mass and launch vehicle requirements for the baseline missions studied for the 1981-1988 opportunities. For comparison, two lower priority, less costly mission configurations are shown. If available, the shuttle opens the door for many additional possibilities, not the least of which are combinations of the individual missions into single missions. The reality of this possibility must be borne in mind in future studies of this kind.

TABLE XVII.- SRT REQUIREMENTS

VOIR

- Expanded radar mapper capabilities - multispectral radar, stereographic techniques, dual polarization
- Complementary experiment capabilities - gravity subsatellite, microwave radiometry, radio science
- Auxiliary experiment capabilities - solar-wind interaction, aeronomy, improved remote-sensing capabilities (broad-band spectrometry, short-term imaging)
- Laboratory studies - high-temperature effects on soil properties (dielectric constant, etc.)
- Spin-stabilized spacecraft radar mapping, UV line-scan imaging systems

Lander

- Short (~1 hr) and medium (8-20 hr) lifetime lander designs
- Mission analyses - multiple short-life landers, mixed short- and medium-life landers, shuttle/IUS applications, gravity-assist mission applications, simultaneous orbiter mission
- Science instruments - γ-ray spectrometry and x-ray fluorescence techniques for short- and medium-life lander applications; advanced techniques for longer-lived landers above plus age-dating techniques, solar tide-measuring system
- Long (~ days) life lander systems - high-temperature systems and electronics, cooling systems
- Auxiliary experiment capabilities - atmospheric entry experiments

Entry Probe

- Probe system design - lifting probe, zoom-climb trajectories; orbital deployment
- Mass spectrometer - free radical analyses, 4-km/sec inlet speed sampling in free molecular and continuum flow
- Cloud characterization - condensibles and dust cloud composition, advanced techniques for particle size, shape, and number density
- Radar altimeter - lightweight (~5 kg)
- Auxiliary experiments - geochemical lander instruments

Balloon

- Balloon systems - new concepts and techniques for longer life at lower altitudes (~30 km), new skin materials, deployment techniques, power systems (RTG, battery), RTG interactions, packaging and inflation techniques, high-temperature electronics
- Instruments - cloud characterization devices
- Dropsondes - design, instruments
- Auxiliary experiments - geochemical lander (dropsonde) instruments

TABLE XVIII.- LAUNCH MASS REQUIREMENTS

Mission	Launch mass, kg	Launch vehicle
VOIR (1981)	2636-3440	TITAN/Centaur-Shuttle/IUS
Lander (1985)	1375	TITAN/Centaur
Entry probe (1988) or	1372	TITAN/Centaur
Balloon (1988)	1512-3138	TITAN/Centaur-Shuttle/IUS
Solar minimum Pioneer Venus orbiter	520	Atlas/Centaur
Pioneer-class VOIR	1055	Atlas/Centaur/TE 364

Another set of options not given much attention in this study is the possibility of piggyback measurements (remote sensing, entry probe, lander, or balloon dropoff) at Venus from a flyby spacecraft dedicated to other solar system objects, for example, Venus gravity-assist missions. Again, these possibilities should be included in future studies when those missions become better defined.

3.0 PRESENT STATE OF KNOWLEDGE

The following presentation is descriptive only and summarily presented; it is not intended to be a scientific review of knowledge concerning Venus. Where possible, emphasis is placed on observational data (or the lack of it) either from Mariners 2, 5, or 10, or Veneras 4-8, or from Earth-based radar, radio, and spectroscopic observatories.

3.1 Solar Wind/Planet Interaction

Evidence for the interaction of the solar plasma and magnetic field with the upper atmosphere and ionosphere of Venus was seen in both Mariner and Venera particles-and-fields experiments (refs. 24-26) and in the Mariner-5 and Mariner-10 radio-occultation experiments (refs. 27 and 28). Not a great deal of quantitative information regarding the interaction is available, however. There is no indication that Venus possesses an intrinsic magnetic field; an upper limit on its magnetic moment of 10^{-4} times that of Earth was provided by the negative magnetometer observations of Mariners 5 and 10 and Venera 4 (this upper limit is equivalent to a surface equatorial field strength of 4γ). Such a low value yields a magnetic pressure much too low to counteract the solar-wind pressure. Thus, unlike the Earth (and probably Mars), the interaction is directly with the planetary ionosphere; that is, the simplest model (ref. 29) suggests that the solar-wind dynamic pressure is balanced by the thermal ionospheric static plasma pressure, forming an anemopause (or ionopause). Figure 6 illustrates the location of the bow shock and ionopause as determined by Mariners 5 and 10 and Veneras 4 and 6 (ref. 26). It is important to note that the locations of these features are functions of solar-wind

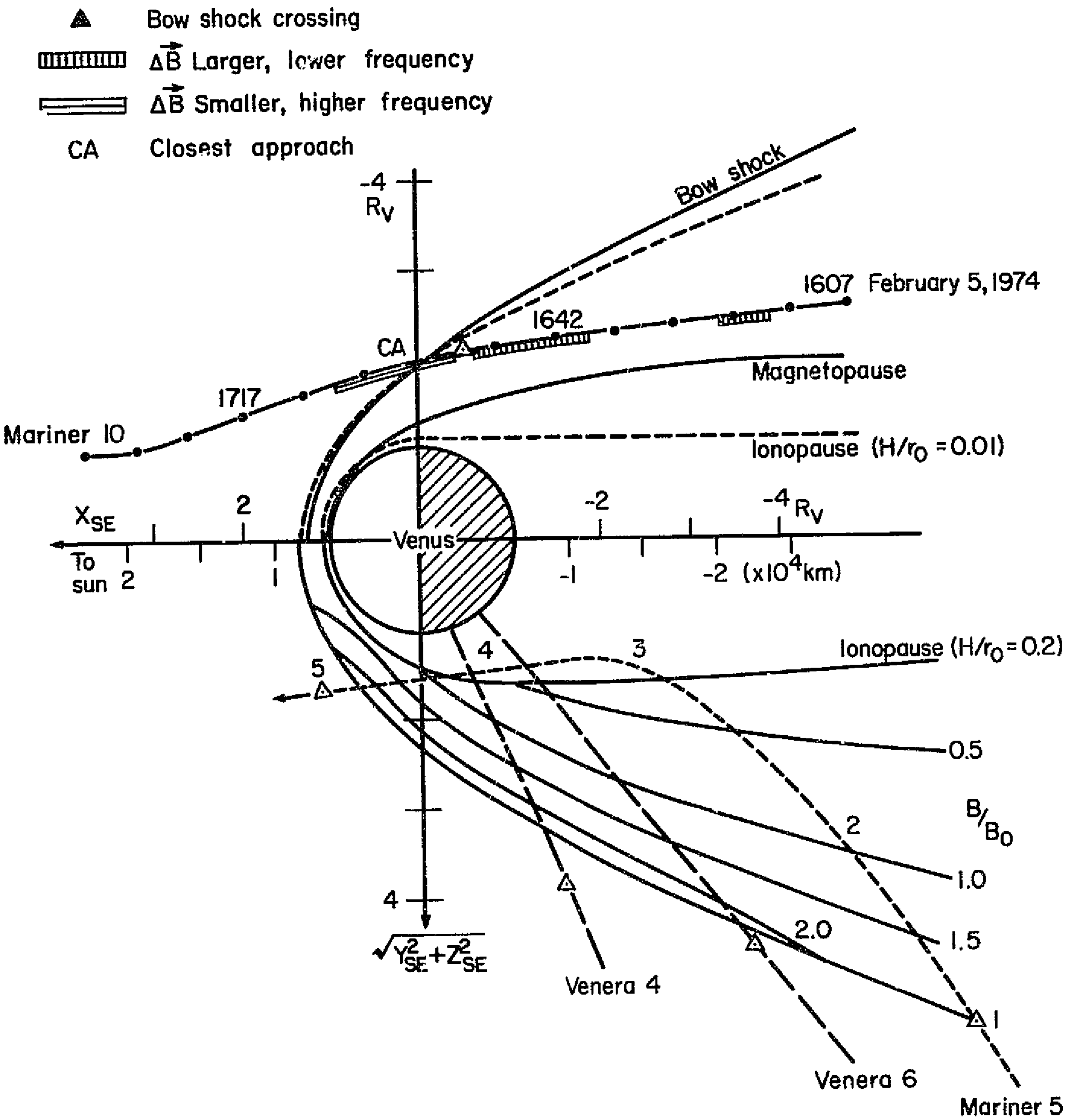

Figure 6.- Solar-wind/Venus interaction.

conditions and ionospheric conditions. Since the latter vary over the sunspot cycle, it is not unexpected that the 1967 solar maximum and 1974 solar minimum results are quite different. A consistent model of the magnetosphere is thus difficult to form at this time. At any rate, it appears that the solar-wind interaction phenomenon at Venus results in a bow shock that stands off some 1500-2000 km from the surface and an ionopause at an altitude of about 300-500 km (near the subsolar point).

3.2 Ionosphere

The vertical electron-density distribution in the ionosphere has been measured by the Mariner-5 and Mariner-10 radio-occultation experiments. Two daytime (solar zenith angle $\chi = 33.3°$, M5; $\chi = 67.0°$, M10) and two nighttime ($\chi = 142.3°$, M5; $\chi = 117.7°$, M10) profiles were measured. The Mariner-5 profiles are shown in figure 7 (ref. 27); the Mariner-10 profiles are shown in figure 8 (ref. 28); the Mariner-5 and -10 daytime profiles are compared in figure 9 (ref. 30) and the uppermost part of the daytime Mariner-10 profile is expanded in figure 10 (ref. 30). Note that all the day and night profiles exhibit peak densities near an altitude of 142 km. The Mariner-5 dayside peak electron density is 5.5×10^5 cm^{-3} compared with 2.9×10^5 cm^{-3} for Mariner 10. The Mariner-5 nightside peak electron density is about 2×10^4 cm^{-3} compared with 9×10^3 cm^{-3} for Mariner 10. (A secondary layer with a peak density of about 7×10^3 cm^{-3} is shown at an altitude of 124 km.) Note that an abrupt decrease in the daytime densities occurs at about 500 km for Mariner 5 and at about 350 km for Mariner 10. These decreases probably represent the location of the ionopause for each case. The difference in ionopause heights and peak densities for Mariners 5 and 10 are probably real and reflect the differences in the solar wind and in sunspot activity from 1967 to 1974 (ref. 31).

Positive-ion species have not yet been observed in the Venus ionosphere. All models assume the existence of CO_2^+, O_2^+, O^+, OH^+, He^+, H_2^+, and H_3^+. Recent models fit to the Mariner-5 and Mariner-10 radio-occultation results are shown in figures 11 (ref. 32) and 12 (ref. 33), respectively. It thus appears that the peak at 142 km is composed of both O_2^+ and CO_2^+ (the former in somewhat greater proportion). The O^+ becomes the dominant constituent above the peak (~250-300 km). Finally, He^+ becomes dominant above that altitude before the abrupt ionopause occurs. The details are all controversial.

3.3 Atmosphere

It is generally convenient in discussions of planetary atmospheres to consider separately the upper atmosphere, which is characterized by molecular diffusion processes, and the lower atmosphere, which is generally uniformly mixed (major constituents) and in thermodynamic equilibrium. The layer or boundary separating these regions is the turbopause, the altitude of which is unknown at Venus but is believed to be in the 110-150 km region (ref. 34). Note that photochemical processes are important at Venus at least down to the cloud-top level (~60 km). For purposes of this discussion, division is made in terms of composition, structure, and dynamics with upper- and lower-atmosphere characteristics noted where pertinent.

3.3.1 Composition - Because Venus is completely covered by clouds, Earth-based measurements bearing on the composition of the atmosphere have been difficult. In spite of the obscuration by the clouds, many excellent measurements have been made using optical techniques (refs. 3 and 34), and a great portion of the data obtained remains unmodified by recent spacecraft measurements.

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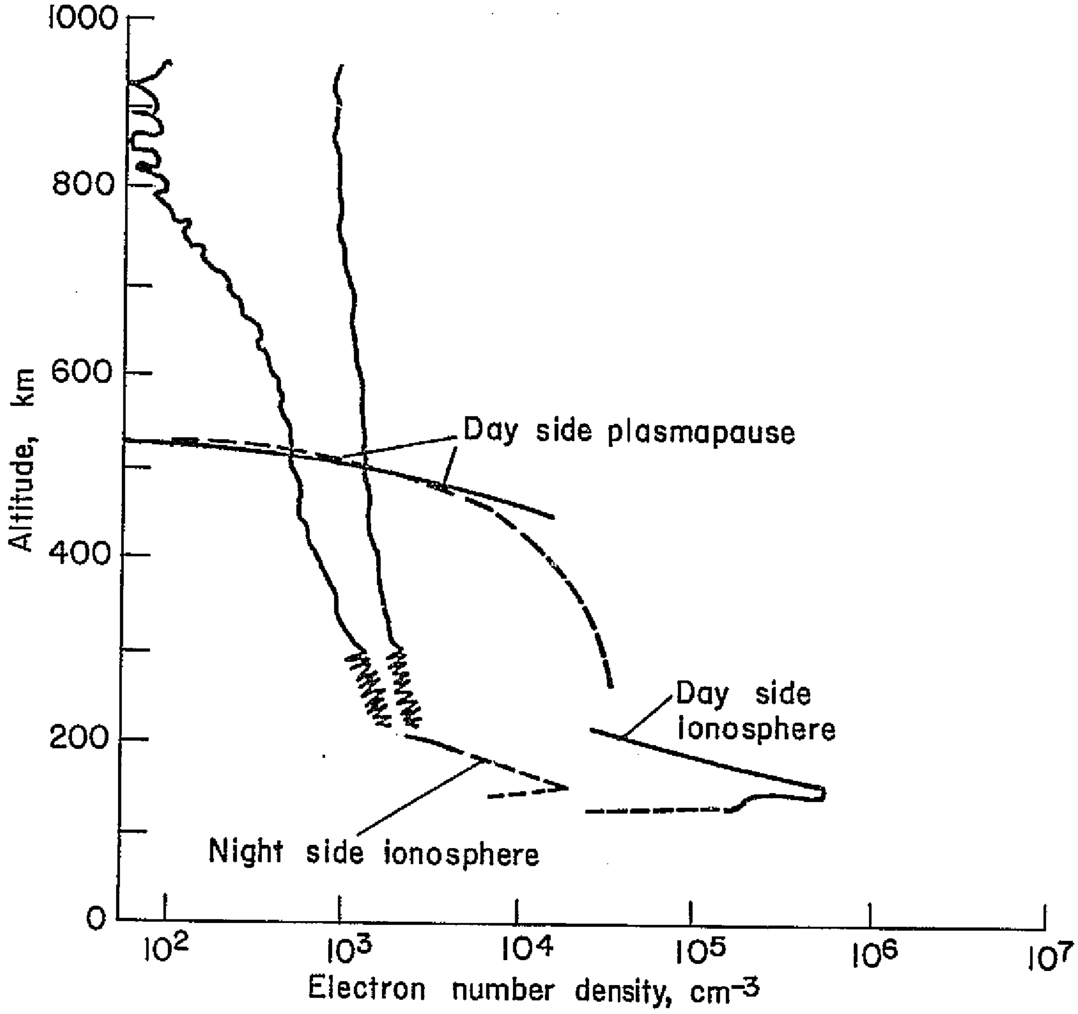

Figure 7.- Mariner-5 electron density profiles.

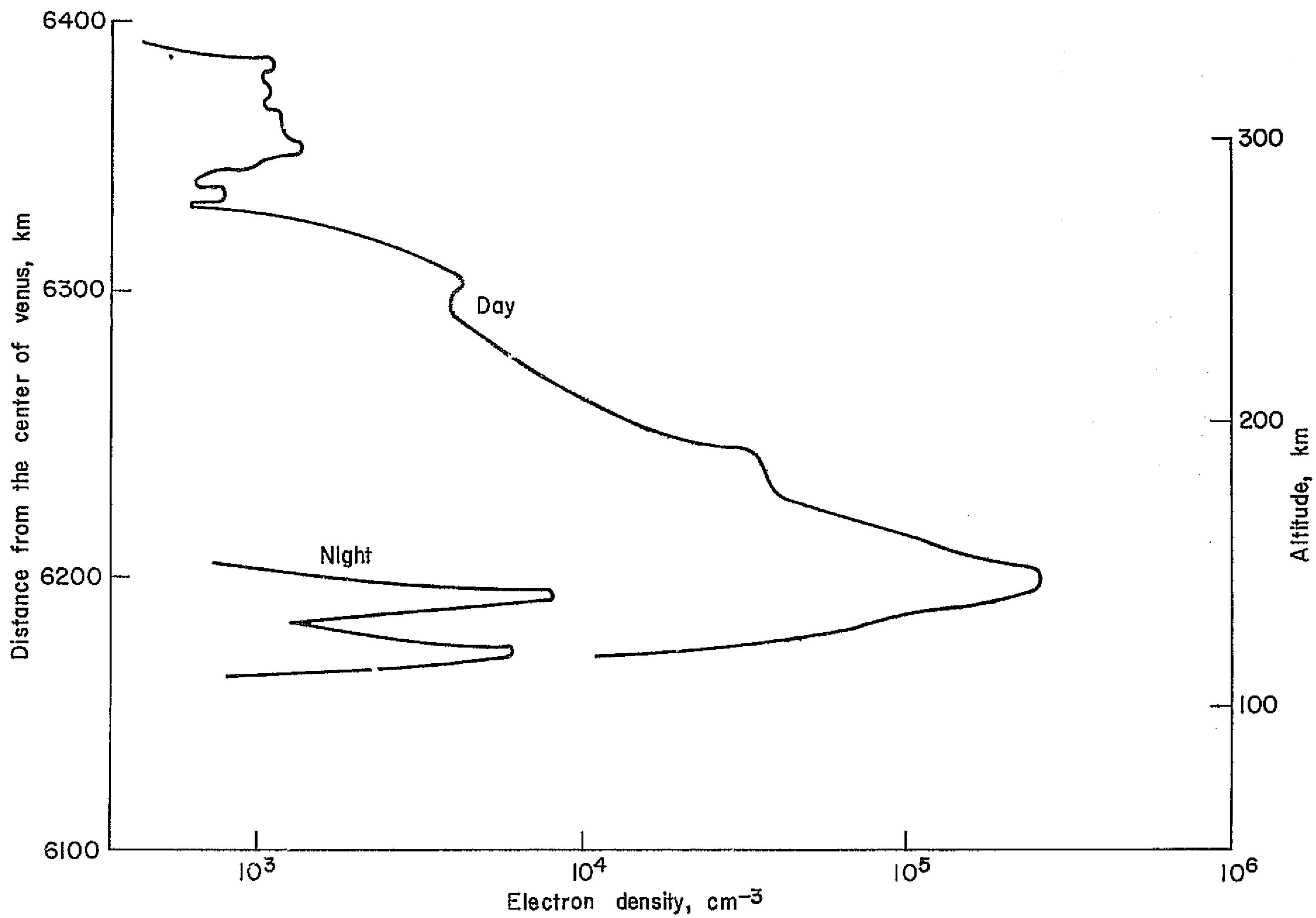

Figure 8.- Mariner-10 electron density profiles.

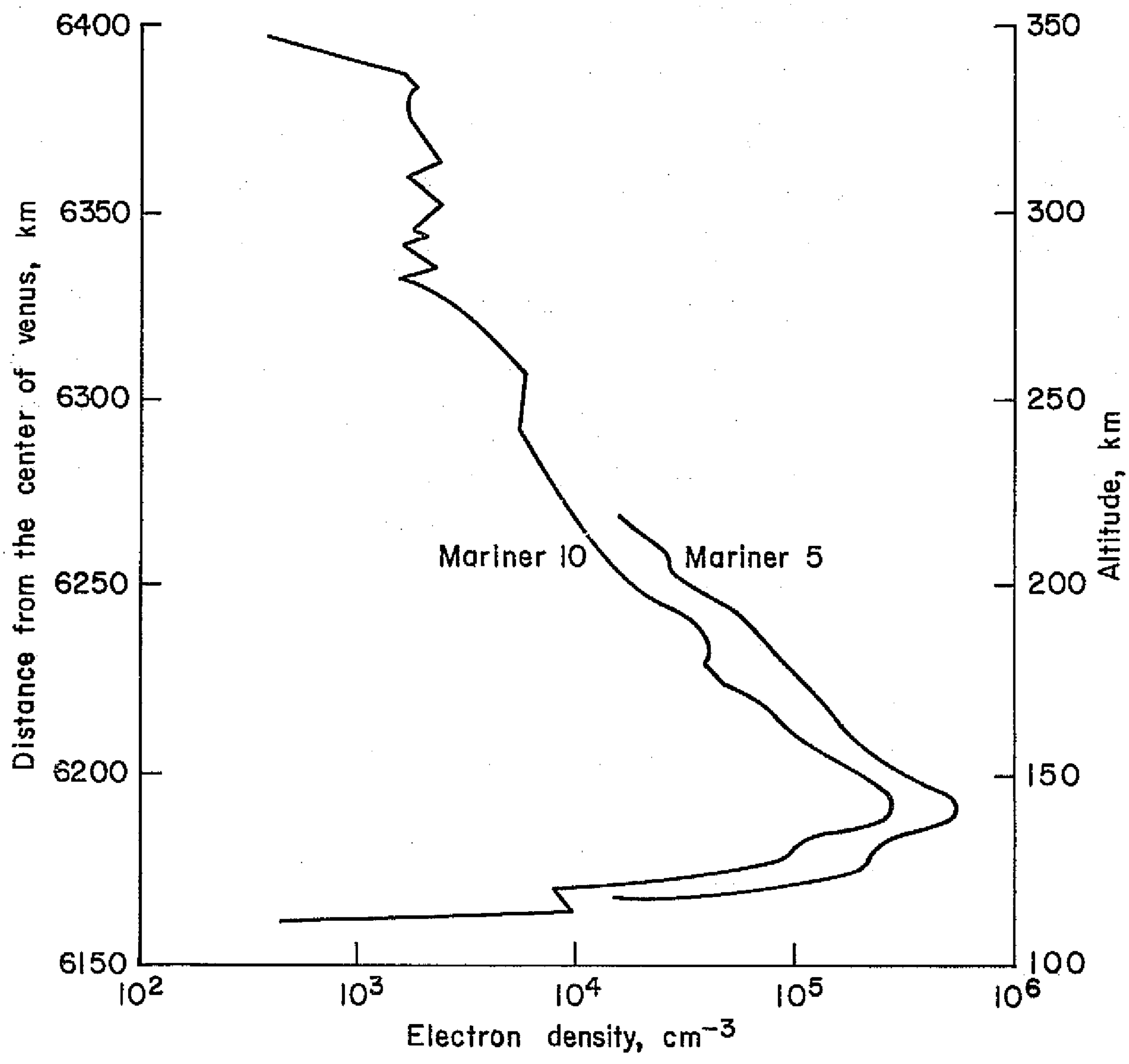

Figure 9.- Mariner-5 and -10 electron density profiles.

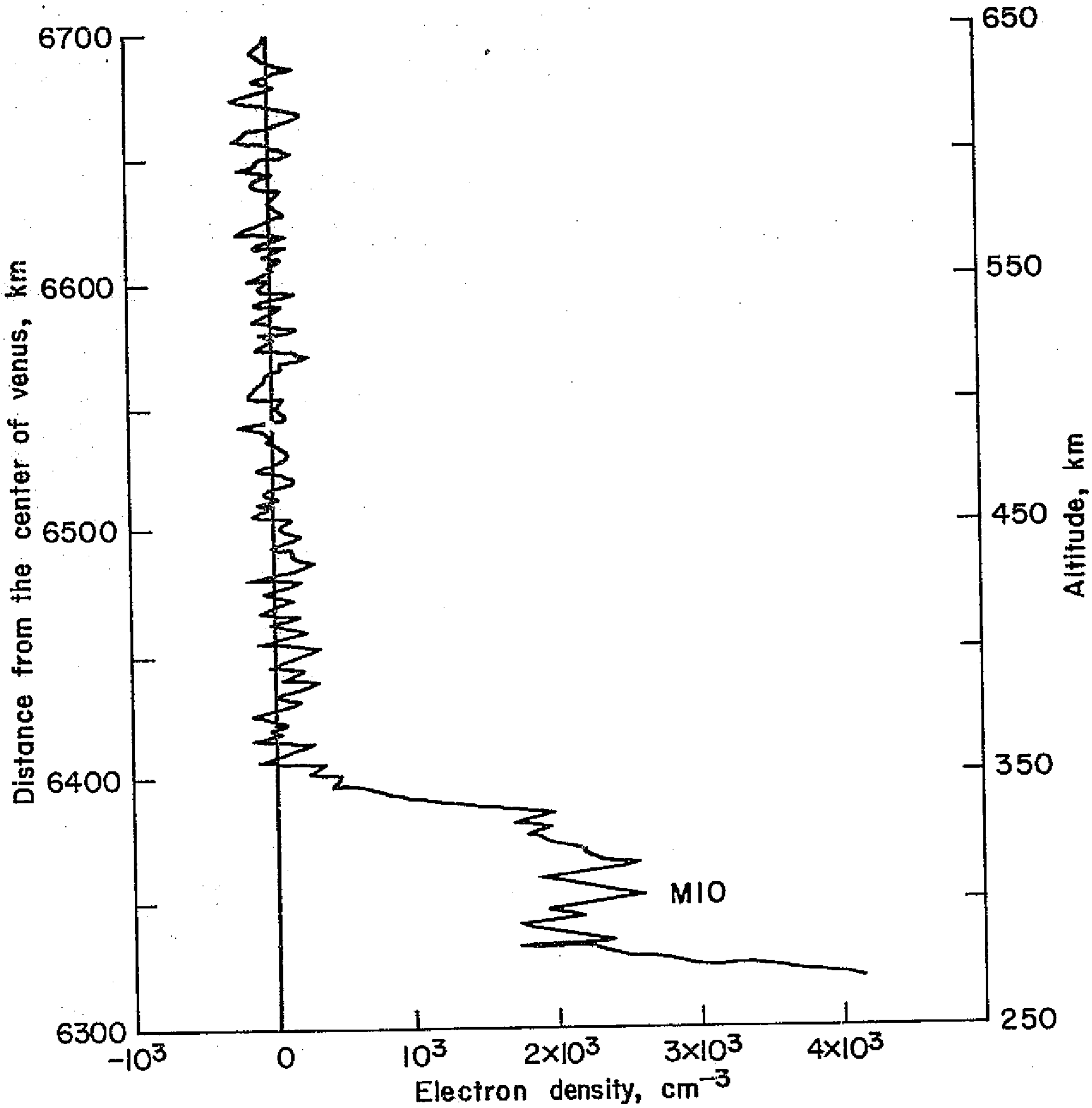

Figure 10.- Mariner-10 topside electron density profiles.

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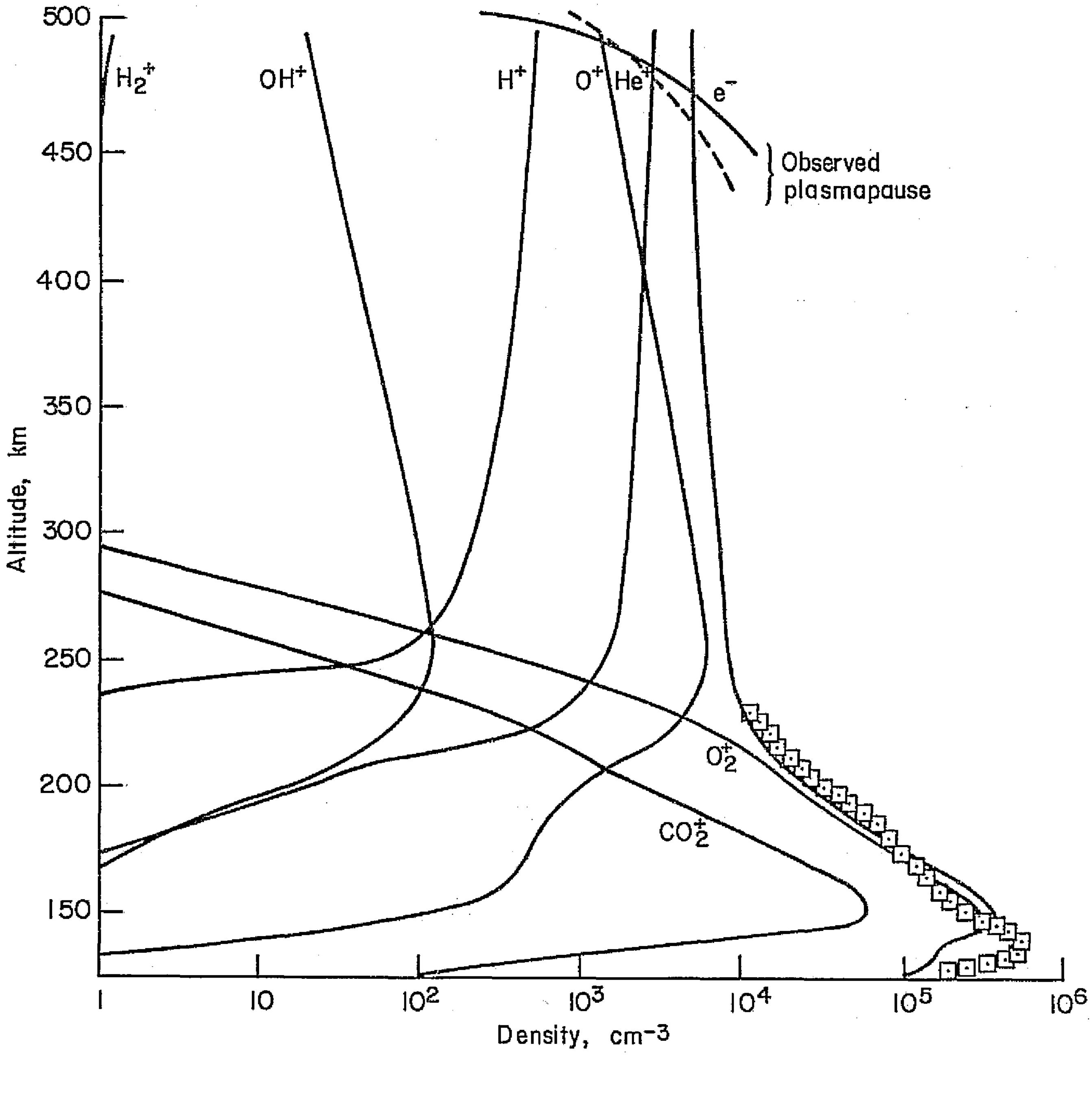

Figure 11.- Model ion density profiles (1).

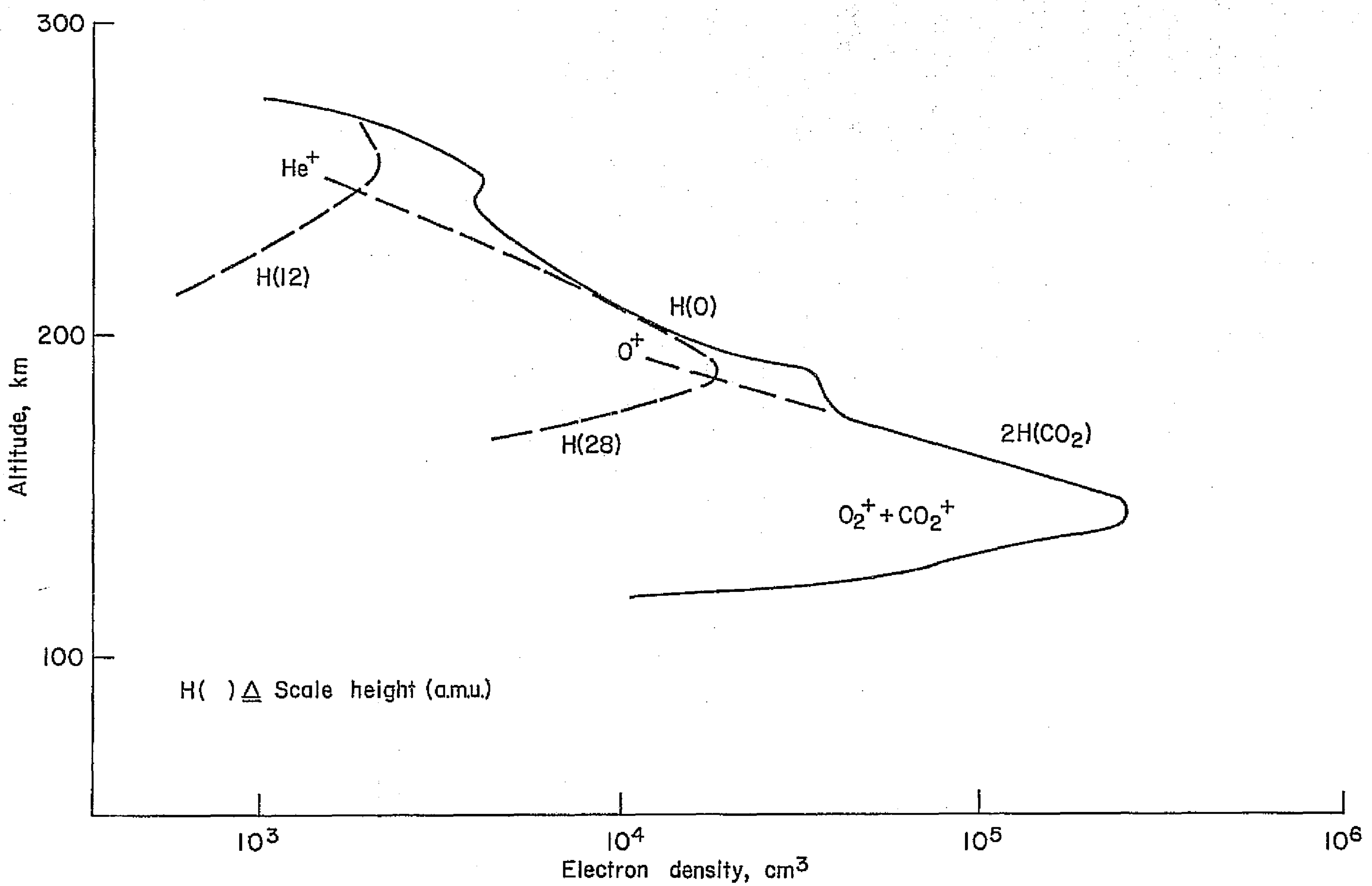

Figure 12.- Model ion density profiles (2).

Earth observatory measurements made prior to the Mariner and Venera flights indicated that CO_2 was likely to be the primary constituent of the atmosphere above the cloud tops. A density scale height of 5.4 ± 0.2 km in the region of the cloud tops was obtained by the Mariner-5 occultation experiment (ref. 35). From independent temperature estimates at this level, it was deduced that this scale height corresponds to a CO_2 fractional concentration of 69 to 87 percent. Venera-4 measurements (ref. 36) led to the conclusion that the lower atmosphere was composed primarily of CO_2 (90-percent CO_2).

Observations from Earth also detected trace quantities of CO, H_2O, HF, and HCl above the cloud layer (refs. 37-39). Of these, the presence of CO above the clouds was confirmed by Mariner-10 measurements (ref. 40) and H_2O below the clouds by Venera-4 data (ref. 36). With the exception of the Venera measurements of H_2O, all water-vapor measurements have been made from Earth, either from the ground (refs. 37 and 39), from balloons (ref. 41), or from high-altitude aircraft (ref. 42). These measurements are very difficult, and they have produced diverse results and interpretations.

Both Mariner-5 and Venera-4 ultraviolet photometers were designed primarily to detect Lyman-alpha emission from atomic hydrogen and 1304-Å resonance radiation from atomic oxygen (refs. 43 and 44). No 1304-Å O-atom radiation was observed by either spacecraft. Strong Lyman-alpha emission was observed by Mariner 5 from about 2 or 3 planetary radii down to the dark limb. Although less intense by a factor of 2, this emission was also observed by Mariner 10 (ref. 40). Venera 4 also observed Lyman-alpha emission but also at less intensity, and the atomic-hydrogen densities calculated from the Venera-4 data (ref. 44) are generally an order of magnitude smaller than those calculated from the Mariner-5 data for altitudes below 900 km (refs. 45 and 46). The Mariner-5 Lyman-alpha intensity shows a definite slope change at a radial distance of 9000 km. The scale height of the signal measured below this level is half that of the signal above. It has been suggested that the smaller scale height arises from either resonance scattering of solar Lyman-alpha from deuterium or from photodissociative excitation of H_2 (ref. 47). If H_2 is responsible for the observed emission, the required H_2 density at 450 km is about 10^{10} cm^{-3} (ref. 48). Such large H_2 concentrations introduce several inconsistencies with known atmospheric characteristics and processes (ref. 49). The deuterium explanation for the lower scale height requires a D/H concentration ratio of about 10 near the base of the exosphere at about 450 km. With an exospheric temperature of 650° K, this results in a D/H ratio in the lower (mixed) region of the atmosphere of 5×10^{-4}. This is within a small fraction of the natural deuterium abundance existing on Earth and, even though a D/H ratio of 10 at 450 km appears abnormally high, it is, in fact, very normal (ref. 48). Neither the H_2 nor deuterium explanations have enjoyed acceptance by the scientific community. An instrument problem cannot be ruled out, either.

Although Mariner 5 was not able to detect atomic-oxygen 1304-Å emission, rocket-borne photometers (ref. 50) and the Mariner-10 ultraviolet spectrometer (ref. 40) have measured such emission from O-atoms, and Venera-4 measured a molecular-oxygen mixing ratio of about 1 percent in the lower atmosphere (refs. 17 and 36). Veneras 5 and 6 did not detect any O_2 nor has O_2 been observed above the cloud layer by observation of molecular-oxygen A-bands from Earth.

Veneras 4-8 gave the first direct measurements of the composition below the cloud layer (ref. 17). The combined results of these measurements showed the lower atmosphere to be 93-100 percent CO_2, less than 1 percent H_2O, less than 0.1 percent O_2, and less than 3-5 percent N_2 (ref. 5). No direct evidence of Venusian atmospheric N_2 or N has ever been obtained. Although a 3-percent N_2 composition appears small, this composition represents an N_2 partial pressure at the surface of about 3 atm. Also note that, although a 0.1-percent H_2O composition represents more water than is present in the atmosphere of Earth, it is only 10^{-4} of the water contained in Earth's oceans. An upper limit of 0.2 percent for the water-vapor mixing ratio in the lower atmosphere has been obtained by comparison of theoretical and observed microwave brightness temperatures at the 1.35-cm water-vapor line (ref. 51). By Earth standards, Venus is a very dry planet. A strongly hygroscopic cloud material such as H_2SO_4 may be responsible for the dry atmosphere (refs. 42, 52, and 53). Venera 8 also indicated the presence of NH_3 in the lower atmosphere, but this observation is not widely accepted by U. S. S. R. and U. S. scientists (refs. 54 and 55).

In addition to Lyman-alpha and O-1304-Å emission, Mariner 10 detected radiation at wavelengths corresponding to resonance radiation from He, Ne, Ar, CO, and C (ref. 40). These wavelengths all lie in the vacuum-UV region and can be observed only from outside the Earth's atmosphere.

Mariner 10 also made measurements of the total undispersed radiation in two zeroth-order channels covering the regions from 200 to 1500 Å and from 1150 to 1700 Å. A surprising aspect of these measurements is the large zeroth-order signal. This signal is greater by a large factor than the sum of signals from all the individual channels and is greater than the Lyman-alpha signal by at least an order of magnitude. Mariner-5 UV measurements were made with a three-channel photometer with short-wavelength cutoffs at 1050, 1250, and 1350 Å and all with long-wavelength cutoffs at 2200 Å (ref. 43). If this unidentified radiation had also been observed by Mariner 5, then either all Mariner-5 channels should have recorded the same signal or the Mariner-5 Lyman-alpha signal should be more than an order of magnitude larger than the Mariner-10 Lyman-alpha signal; neither was the case. In the sunlit atmosphere above the bright limb, the Mariner-5 short-wavelength channel was about two orders of magnitude greater than either of the other two channels (which recorded approximately equal intensities). Also, the Lyman-alpha signals for Mariners 5 and 10 agreed, to within a factor of 2 to 4, for planetocentric distances greater than 7000 km. The large unidentified zeroth-order signal of Mariner 10 remains unexplained.

The most surprising result of the studies of the past decade or so is the small amounts of CO and O detected in the atmosphere. Consequent speculations are that the CO_2 is in some manner rapidly reformed, that the dissociation products enter into further reactions, or that the dissociation products are rapidly transported downward in the atmosphere (refs. 56-58).

Current knowledge of the composition of the atmosphere of Venus is given in table XIX. In summary, the atmosphere is composed of at least 90-percent CO_2 (probably more like 97 percent), less than 7-percent N_2, about 1-percent O_2, and a few hundredths (or less) percent H_2O. Trace quantities of CO, HF, and

TABLE XIX.- VENUS ATMOSPHERE COMPOSITION (EARTH COMPARISON IN PARENTHESES)

Component	Percent by volume	Source	Component	Percent by volume	Source
CO_2*	97 (3×10^{-2})	Venera	C_2H_2	$<10^{-4}$	Spect.
N_2, A, inert gases?	<2 (79)	Venera	HCN	$<10^{-4}$	Spect.
O_2?	$<8\times10^{-3}/<10^{-1}$ (21)	Spect. (upp. lim.)/Venera	O_3	$<10^{-6}$ ($<10^{-5}$)	Spect.
H_2O*	10^{-4}-10^{-2}/10^{-2}-10^{-1} (<1)	Spect./Venera	C_3O_2	$<5\times10^{-5}$	Spect.
HCl*	6×10^{-5}	Spect.	H_2S	$<2\times10^{-2}$	Spect.
HF*	5×10^{-7}	Spect.	SO_2	$<3\times10^{-6}$	Spect.
CO*	4.6×10^{-3} (10^{-5})	Spect.	CH_3F	$<10^{-4}$	Spect.
CH_4	$<10^{-4}$ (1.5×10^{-4})	Spect.	HBr, HI	$<10^{-1}$	Est.
COS	$<10^{-6}$-10^{-4}	Spect.	Hg	13^{-3}-10^{-1}	Est.
NH_3?	$<3\times10^{-6}/10^{-2}$-10^{-1}	Spect./Venera	HgBr	10^{-3}	Est.
N_2O	$<5\times10^{-5}$	Spect.	HgI_2	10^{-3}	Est.
He	$<10^{-2}$ (5.24×10^{-4})	Est.			
CH_3Cl	$<10^{-4}$	Spect.			

*Definitely detected
?Questionable detection

HCl are present at least within the cloud layer. Also, He, Ne, Ar, H, O, CO, and C have been detected above the cloud layer by resonance fluorescence. The primary constituents of the exosphere appear to be atomic hydrogen and helium. The distribution of species above the turbopause is suggested by the model given in figure 13 (ref. 32). (This neutral model was used to construct the ionosphere model produced in figure 11.)

3.3.2 Structure - In spite of the obscuring cloud layer, important information relating to atmospheric structure was obtained by Earth-based observations made before the Mariner and Venera flights. Of particular importance were the microwave, infrared radiometric, and spectroscopic measurements (ref. 34).

Microwave radiation at wavelengths between 3 cm and 45 m passes unattenuated through the Venusian ionosphere, atmosphere, and clouds. Radio telescope measurements of microwave thermal emission from Venus at centimeter wavelengths gave mean surface temperatures of about 750° K (refs. 59-61). Earth observation of the infrared emission from the cloud layer gave a cloud-top temperature of about 235° K. Models based on this cloud temperature suggest cloudtop pressures of about 90 mb. Analysis of equivalent-width measurements obtained from high-resolution interferometer spectra of CO gave a cloudtop temperature of 240° K and pressure of 60 mb (ref. 38).

Measurements of the occultation of Regulus by the atmosphere of Venus gave density, pressure, and scale heights at a radial distance of about 6170 km (ref. 62).

No direct evidence of surface pressure existed before the Mariner and Venera flights; however, models constructed to explain the high microwave-derived surface temperatures predicted surface pressures of ~20 atm for a pure CO_2 atmosphere and several hundred atmospheres for a low CO_2 abundance.

The radio-occultation measurements of Mariners 5 and 10 were used to determine temperature and pressure profiles from 35 km to about 90 km (refs. 28 and 35). The refractivities obtained from the radio measurements are converted to number density for an assumed composition. The number density is integrated, by application of the hydrostatic equation, from the top of the atmosphere to obtain the pressure as a function of altitude. Temperature profiles are then obtained from the gas law, again with recourse to the assumed composition. Integration of the number density requires an assumption of the initial temperature. Above a radial distance of about 6120 km (70-km altitude), temperature profiles depend on the initial assumed temperature; below 70 km, temperature profiles converge even for assumed initial temperatures at 90 km, differing by as much as 100° K (150° and 250° K).

Because of the strong atmospheric refraction, Mariner-5 and -10 radio signals were bent to such a degree that the lowest portion of the atmosphere was not sampled (data extended to an altitude of 33 km for Mariner 5 and to an altitude of 40 km for Mariner 10). Nevertheless, the data were, however, sufficiently linear (log(P) vs. z, T vs. z) to permit extrapolation to the surface. Assuming an adiabatic atmosphere below the 33-km level, extrapolation of Mariner-5 data gives a surface temperature and pressure of 800° K and 100 atm. Subsequent analysis of Mariner-5 data yielded average surface temperatures of 700° K and 100 atm (ref. 63).

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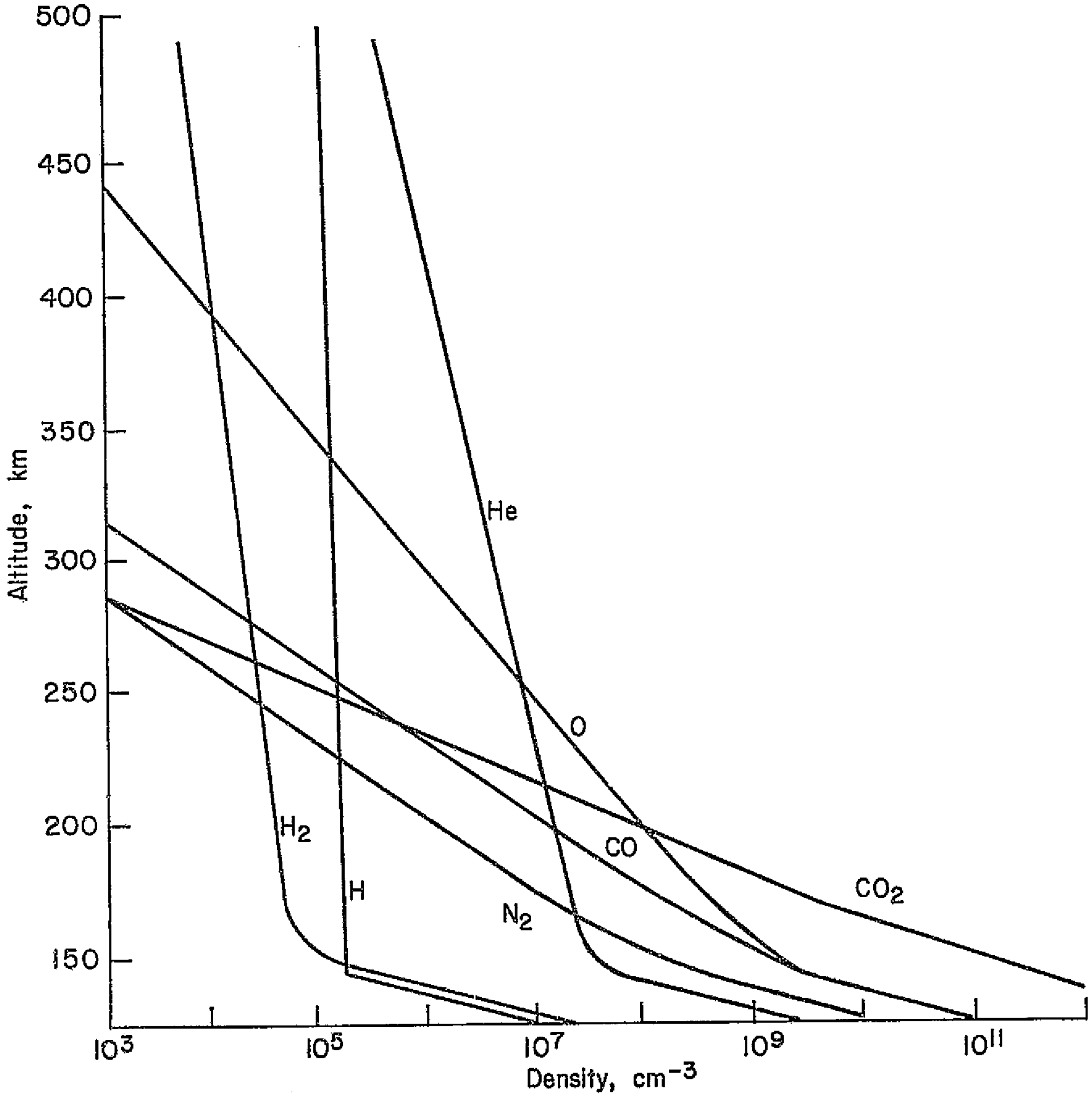

Figure 13.- Model atmosphere.

Venera 4 was originally assumed to have reached the surface of Venus (ref. 17), but later analyses led to the conclusion that it terminated at about 25-km altitude. With this assumption, Venera-4 results are in good agreement with those of Mariner 5. Data from Veneras 5 and 6 spacecraft were received to an altitude of about 20 km. Extrapolation of the data to the surface yielded a temperature of 770° K and a pressure of 97 atm. Venera 7 made a soft landing on the surface of Venus and recorded a surface temperature of 747 ±20° K. (The pressure instrument apparently failed to operate.) A composite picture of the pressure-temperature structure from Mariner 5 and Veneras 4-8 is shown in figure 14 (ref. 17).

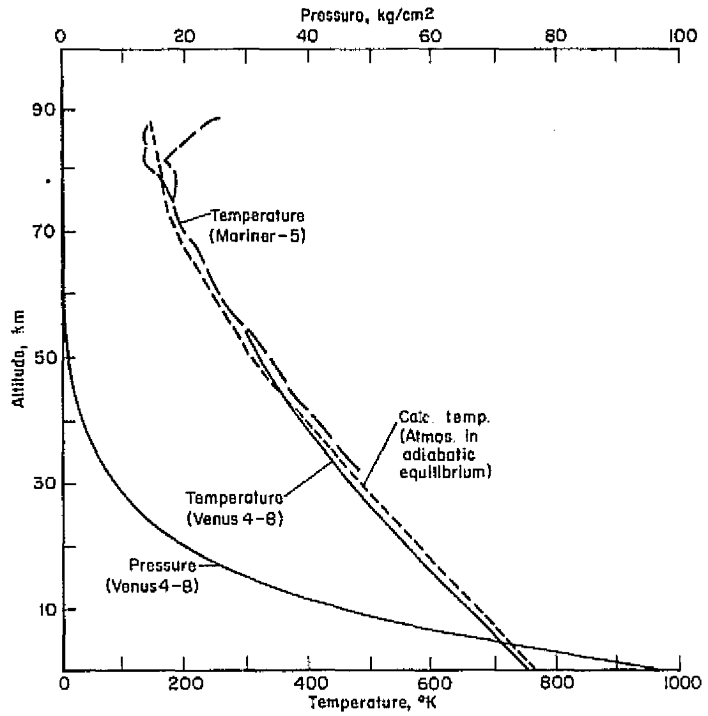

Figure 14.- Venera-4-8, Mariner-5 temperature/pressure profiles.

The exosphere temperature is still somewhat controversial. Models of the atmosphere based on Mariner-5 occultation data yielded exospheric temperatures of about 700° K (refs. 27, 64, and 65). This temperature agrees well with an exospheric temperature of 650 ±50° K obtained from a model based on Mariner-5 measurements of Lyman-alpha radiation (refs. 43 and 46). More recent modeling efforts have shown the experimental data to be consistent with an exospheric temperature of 350°-400° K, however (refs. 32, 66, and 67).

Mariner-10 occultation data, although obtained at a different latitude and solar zenith angle, yielded pressure and temperature profiles (ref. 28) very similar to those obtained from Mariner-5 occultation experiments (fig. 15). These profiles show four distinct temperature fluctuations between altitudes of 56 and 63 km and a sharp drop in lapse rate at 46 km. Somewhat similar variations were observed for Mariner 5, although in a higher altitude region between 60 and 90 km (ref. 68). It is suggested that these abrupt

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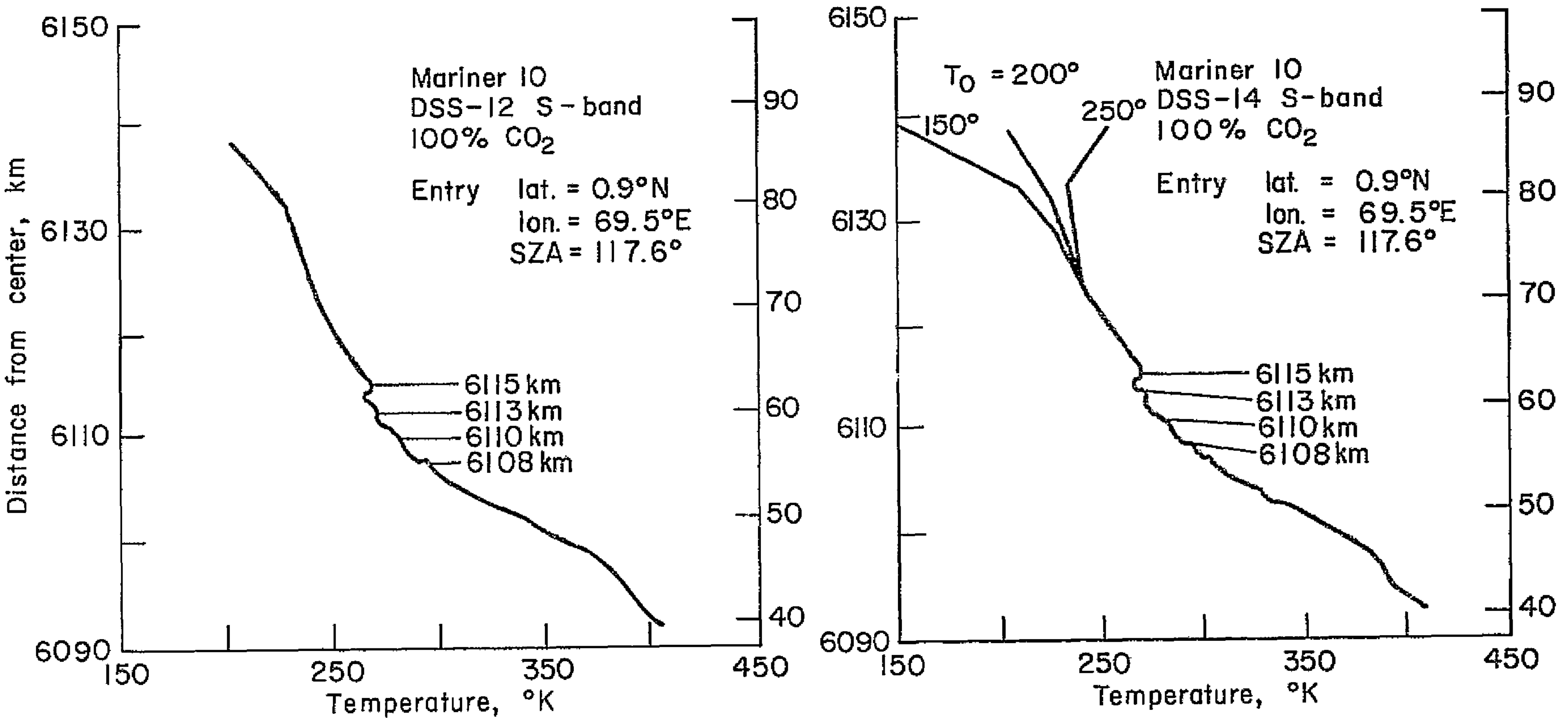

(a) Temperature profile from Mariner 10 S-band closed-loop data received from DSS 12. The initial temperature was 200° K. The temperature inversions are seen to be identical to those of figure 4.

(b) Temperature profiles obtained from Mariner 10 S-band, closed-loop entry data received at DSS 14. The initial temperatures were 150°, 200°, and 250° K. Note the temperature inversions at 6108, 6110, 6113, and 6115 km.

Figure 15.- Mariner-10 temperature profiles.

slope changes in the temperature profile are associated with atmospheric dynamics and cloud structure. Note that the temperatures and pressures at 70-km altitude calculated from the data from Mariners 5 and 10 are about 240° K and 50 mb (ref. 35). These data are in good agreement with cloudtop temperatures and pressures calculated prior to Mariner 5 (ref. 38).

Venera 8 also used pressure and temperature transducers on an atmospheric descent module to obtain the structure measurements from an altitude of about 50 km to the surface (ref. 17). Although the experimental technique is radically different than the occultation measurements of Mariners 5 and 10, the results are in fair agreement. Venera 8 measured a surface pressure of 90 ±1.5 atm and a surface temperature of 741° ±7° K (figs. 16 and 17). Venera 8 measurements started near an altitude of 45 km, below the temperature fluctuations noted by Mariner 10. Near the surface, the lapse rate was found to be 7.9° K/km, which is close to the adiabatic rate. The rate increased smoothly to 9° K/km at 30 km - the same lapse rate as reported for Mariner 10 for the region near 50 km (ref. 28). Venera-8 experimenters reported a mean molecular weight of 43.4 AMU (not directly measured), consistent with the N_2 upper limit of 7 percent reported by Venera 4 (refs. 35 and 36).

Noll and McElroy (ref. 34) presented working models of the atmosphere structure based on the Mariner and Venera results (excluding Mariner 10 and Venera 8). These models are illustrated in figures 18 through 21, which include corresponding Earth and Mars models.

3.3.3 Dynamics - Indirect information on the horizontal and vertical structures of wind fields in the Venus atmosphere has been obtained from experiments aboard Mariner-10 (ref. 69) and Venera-8 (refs. 21 and 70) spacecraft missions. The spacecraft results are consistent with ground-based UV photographic and some spectroscopic observations which indicate that mean retrograde zonal winds of ~100 m/sec exist above altitudes of approximately 50 km (refs. 71-73). Figure 22 illustrates the vertical profile of the zonal winds as derived from Veneras 7 and 8 (ref. 21). The differences between the Venera-7 and Venera-8 profiles are possibly indicative of actual temporal variations in the winds, although the effects of noise cannot be ruled out. Such temporal variations with time scales greater than 1 week are also indicated from the ground-based observations. The results from Mariner 10 indicate that the mean zonal flow increases with latitude, so that at ~50° latitude the mean zonal wind is ~120 m/sec. Beyond about 50° latitude, the zonal motion appears to have a more or less constant angular velocity. A composite picture of the zonal winds is shown in figure 23 (ref. 17).

In addition to information about the zonal winds, Mariner 10 and the series of Venera spacecraft have yielded information on meridional and vertical winds. Data from Mariner 10 indicate that the atmospheric circulation is approximately symmetric about the equatorial plane of Venus (ref. 69). Thus meridional winds can be expected to be quite small in the equatorial regions, and Mariner-10 results appear to preclude meridional velocities greater than about 10 m/sec at any latitude. Since the Venera spacecraft have all landed in equatorial regions, they have not given much information about meridional winds - figure 22 also shows the variation with altitude of vertical winds as

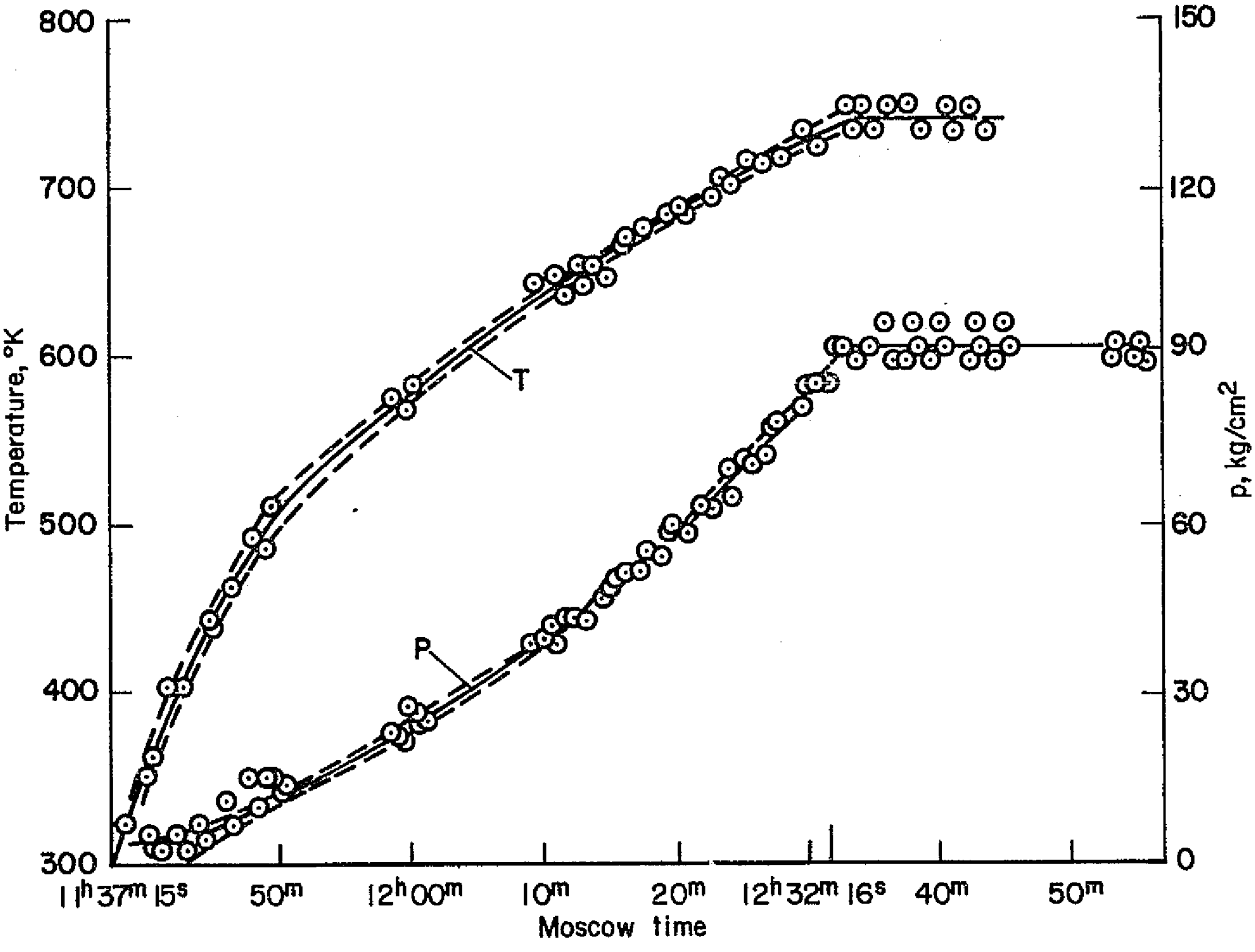

Figure 16.- Results of measurement of temperature and pressure

by Venera-8 spacecraft.

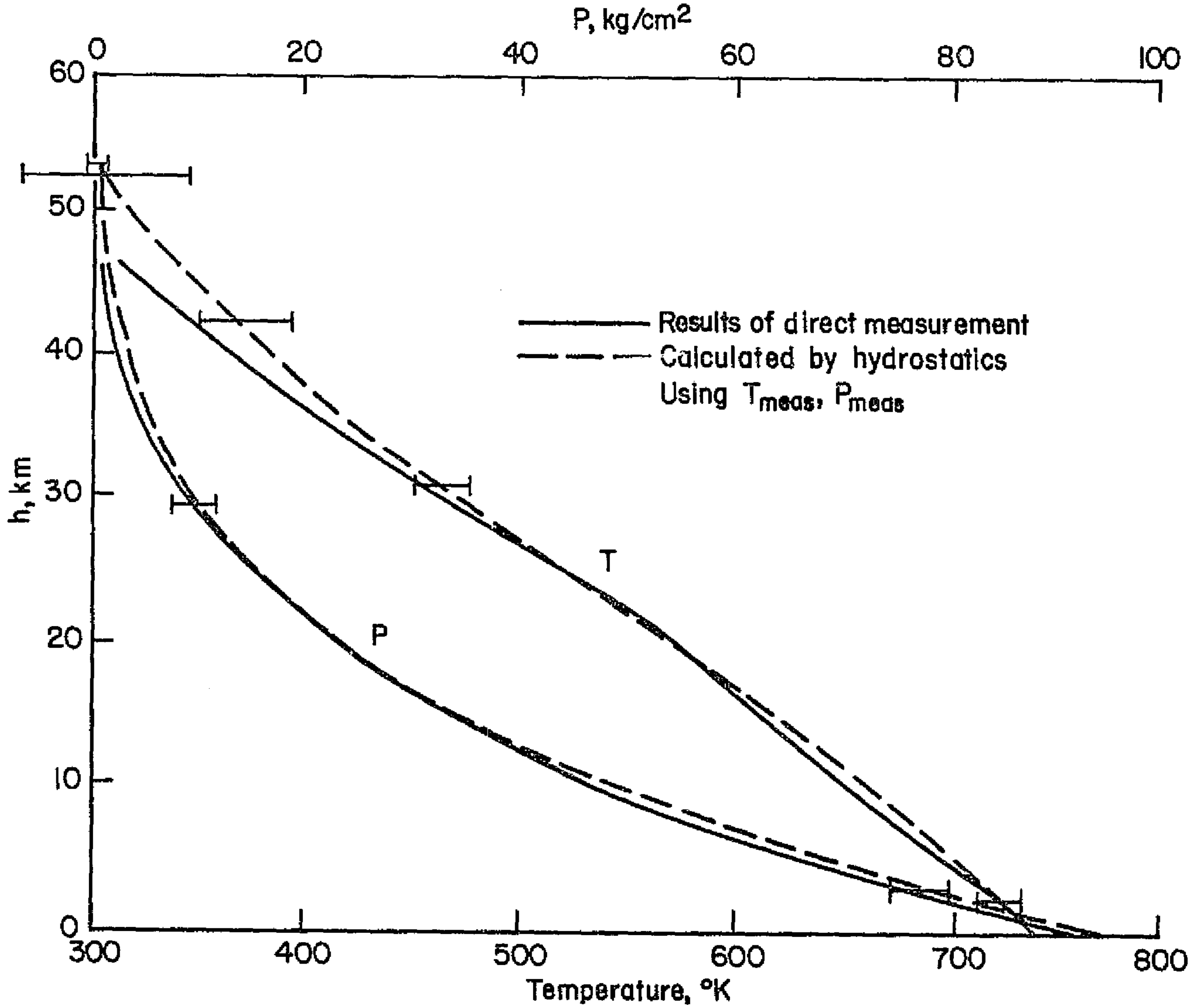

Figure 17.- Altitude profiles of temperature and pressure measured by Venera 8.

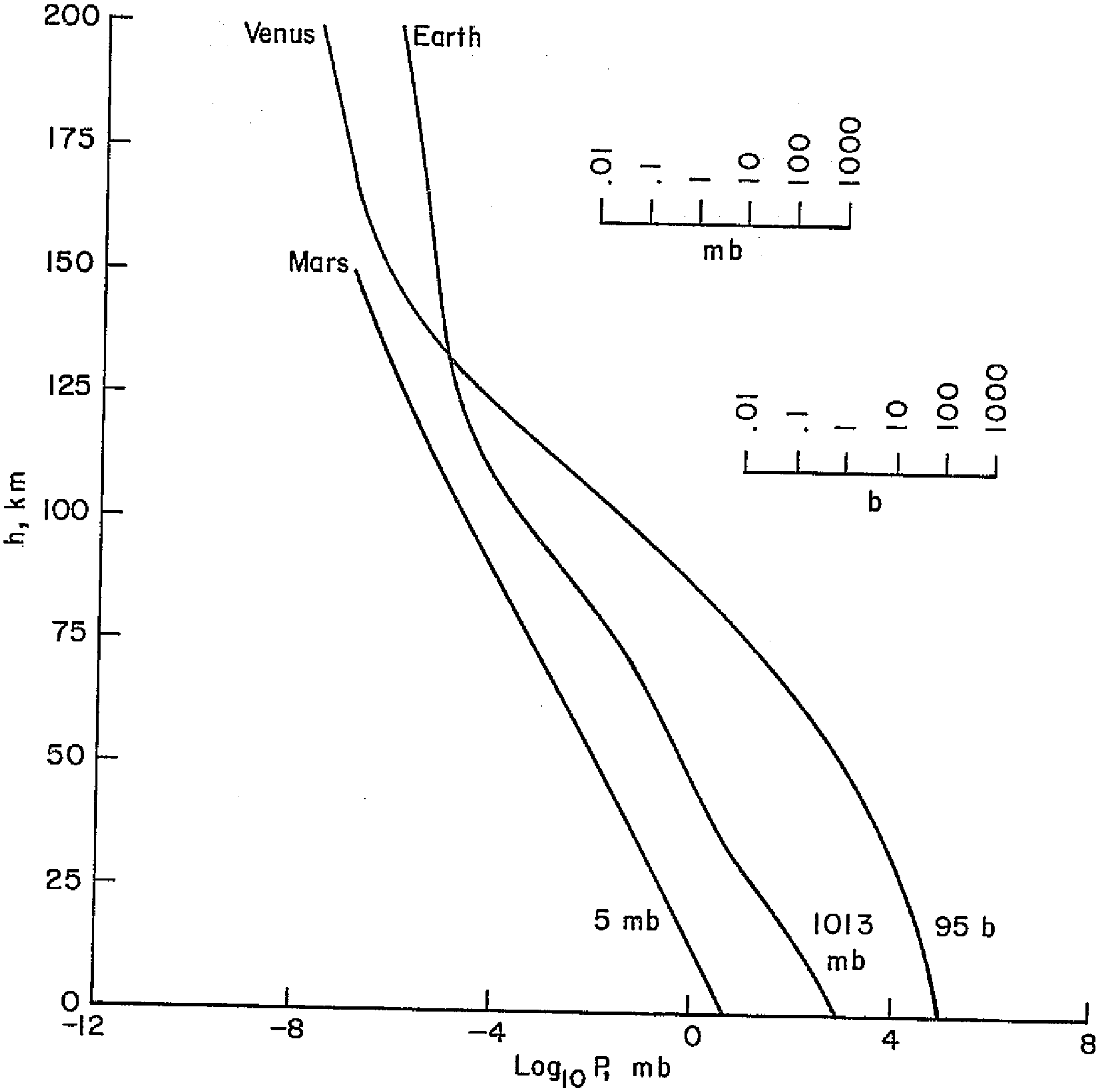

Figure 18.- Atmospheric pressure models - Venus, Earth, Mars.

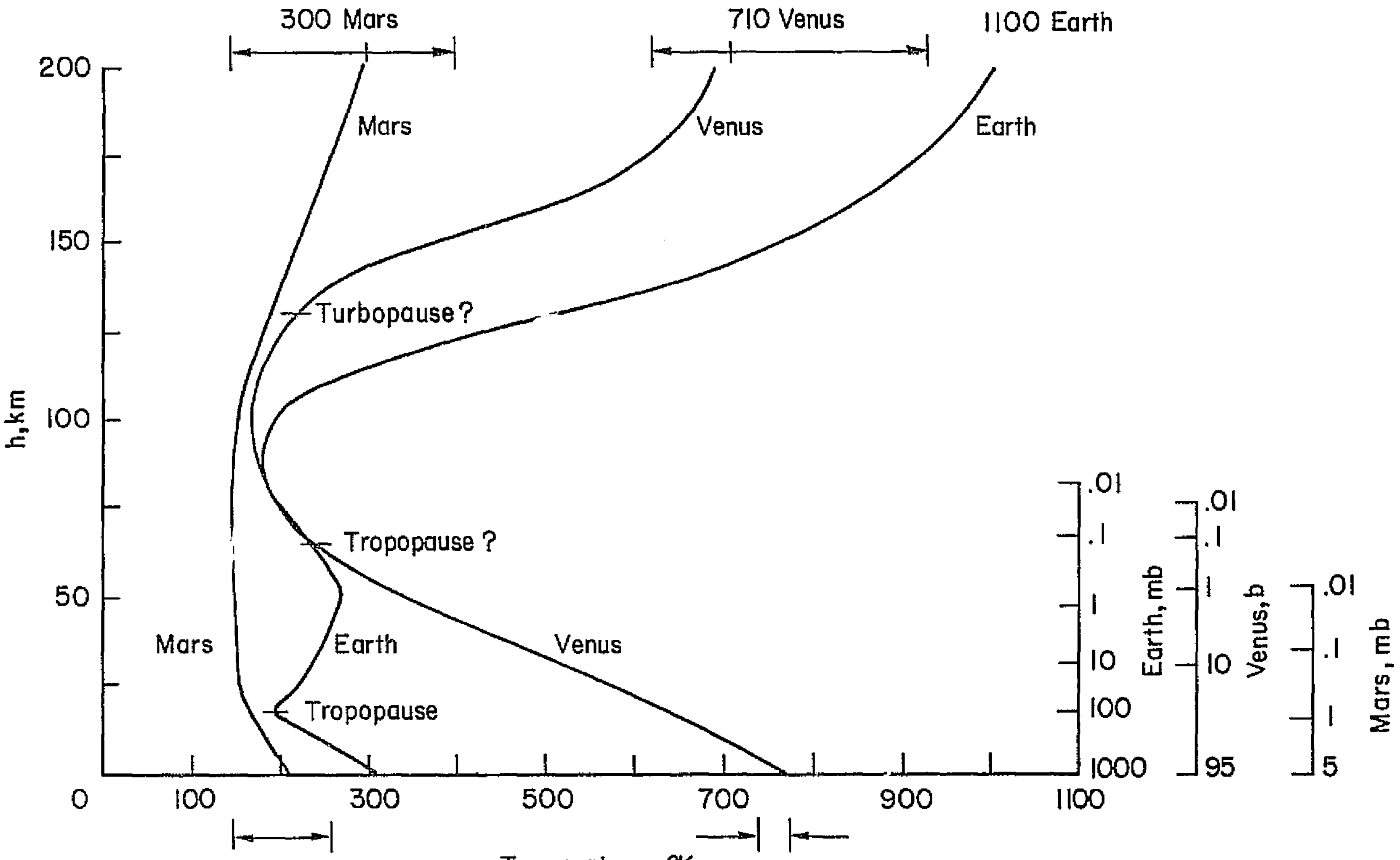

Figure 19.- Atmospheric temperature models - Venus, Earth, Mars.

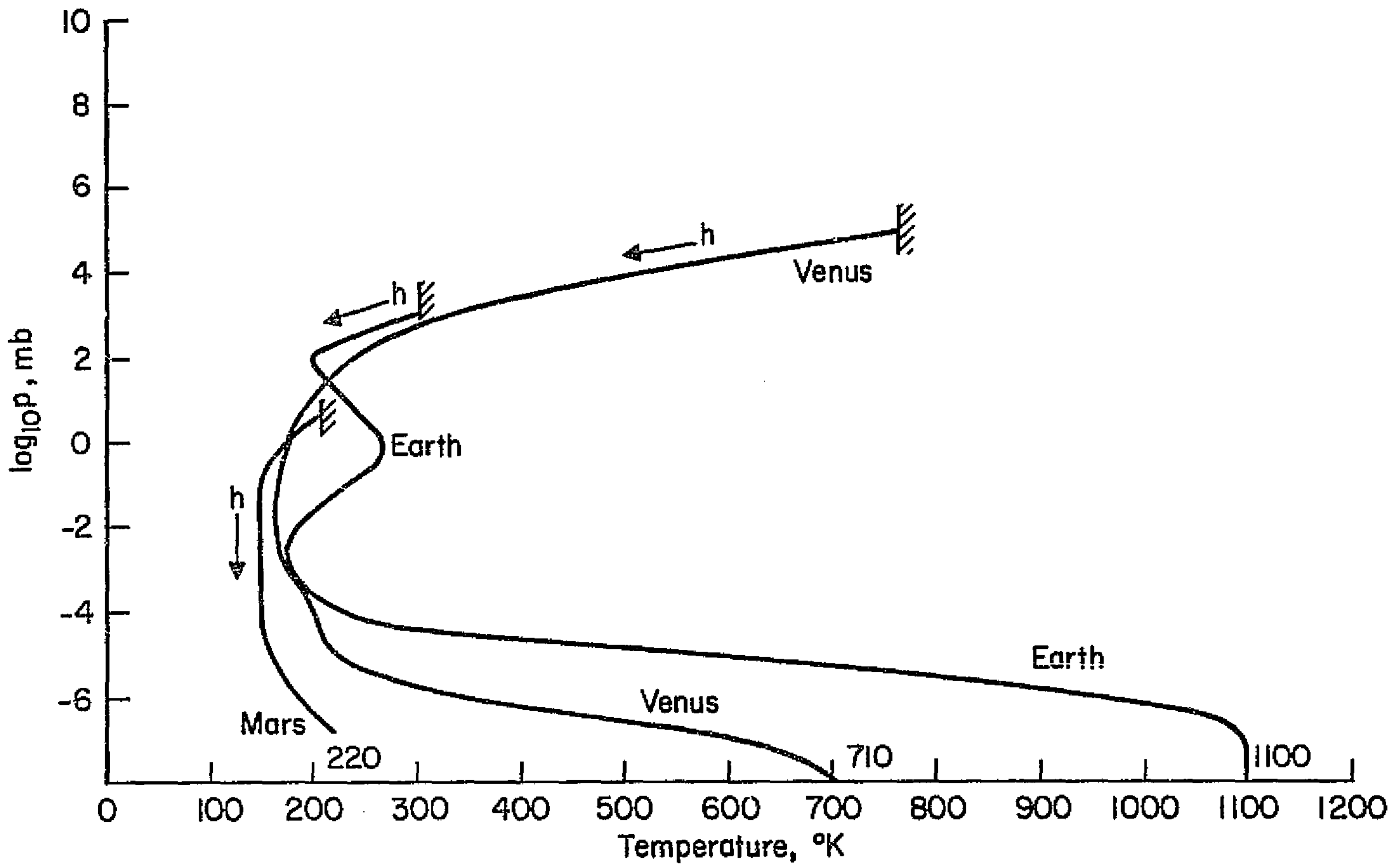

Figure 20.- P-T diagram - Venus, Earth, Mars.

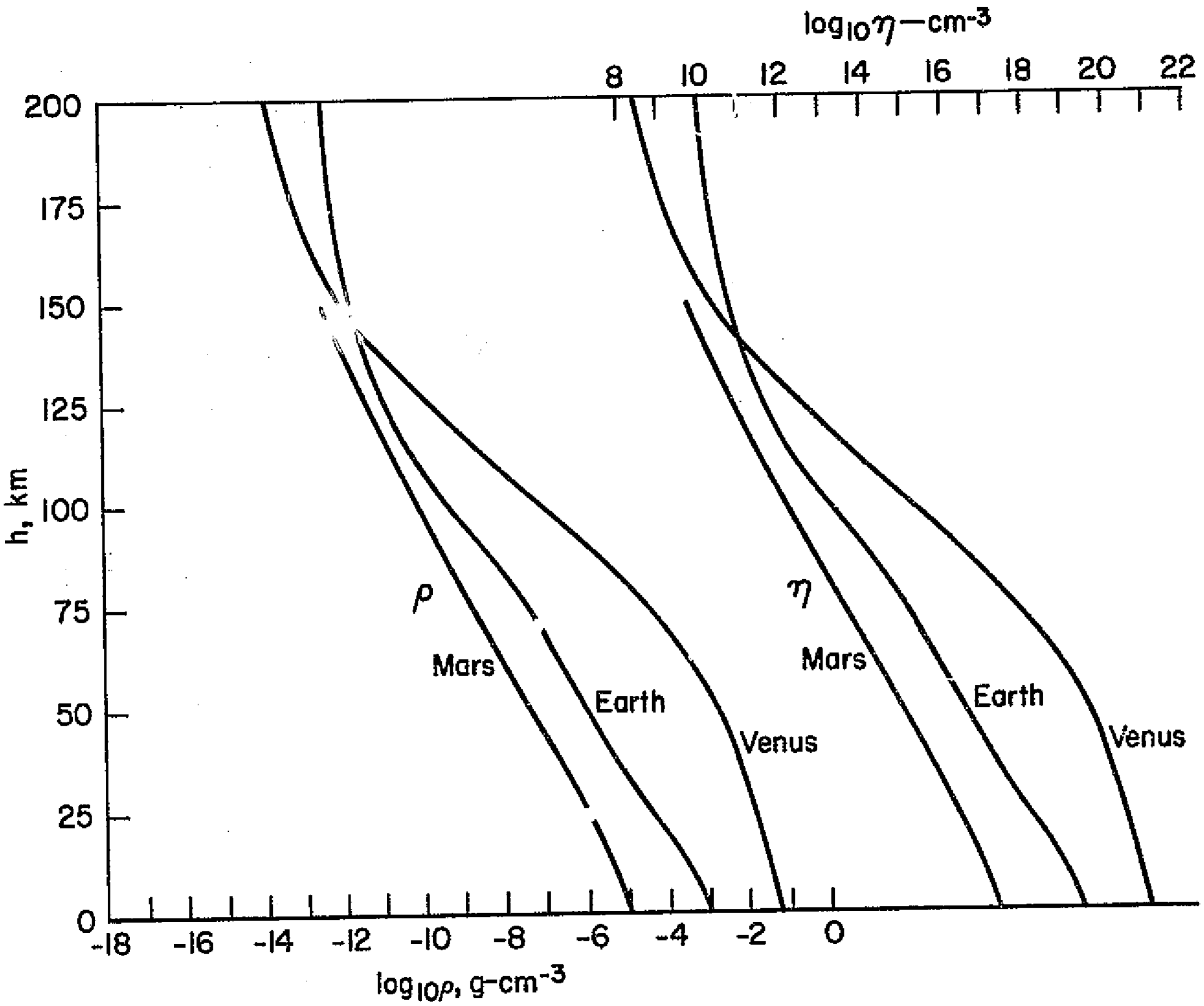

Figure 21.- Atmospheric mass density, ρ, and number density, η, models: Venus, Earth, Mars.

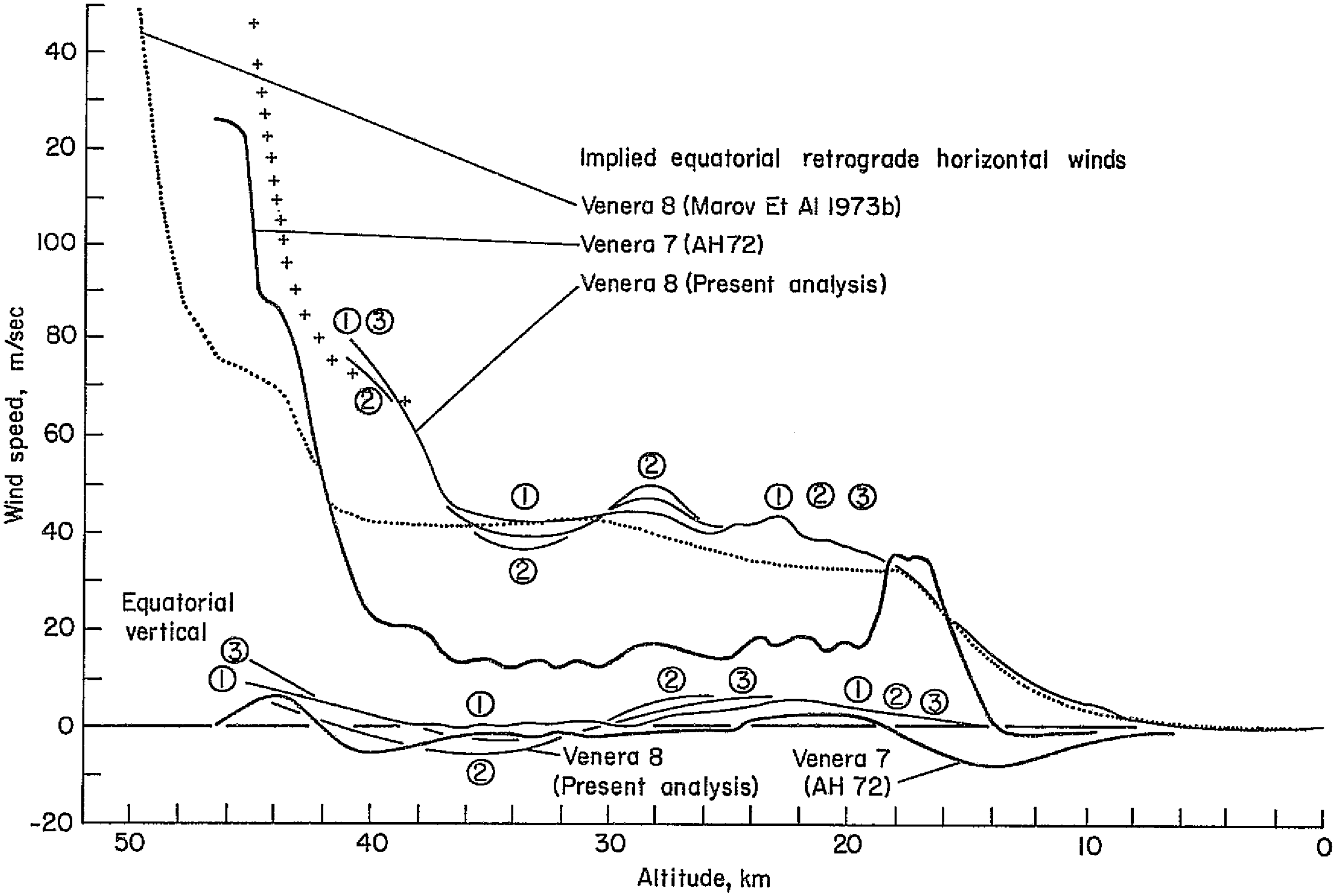

Figure 22.- Vertical profile of the zonal and vertical winds derived from Veneras 7 and 8.

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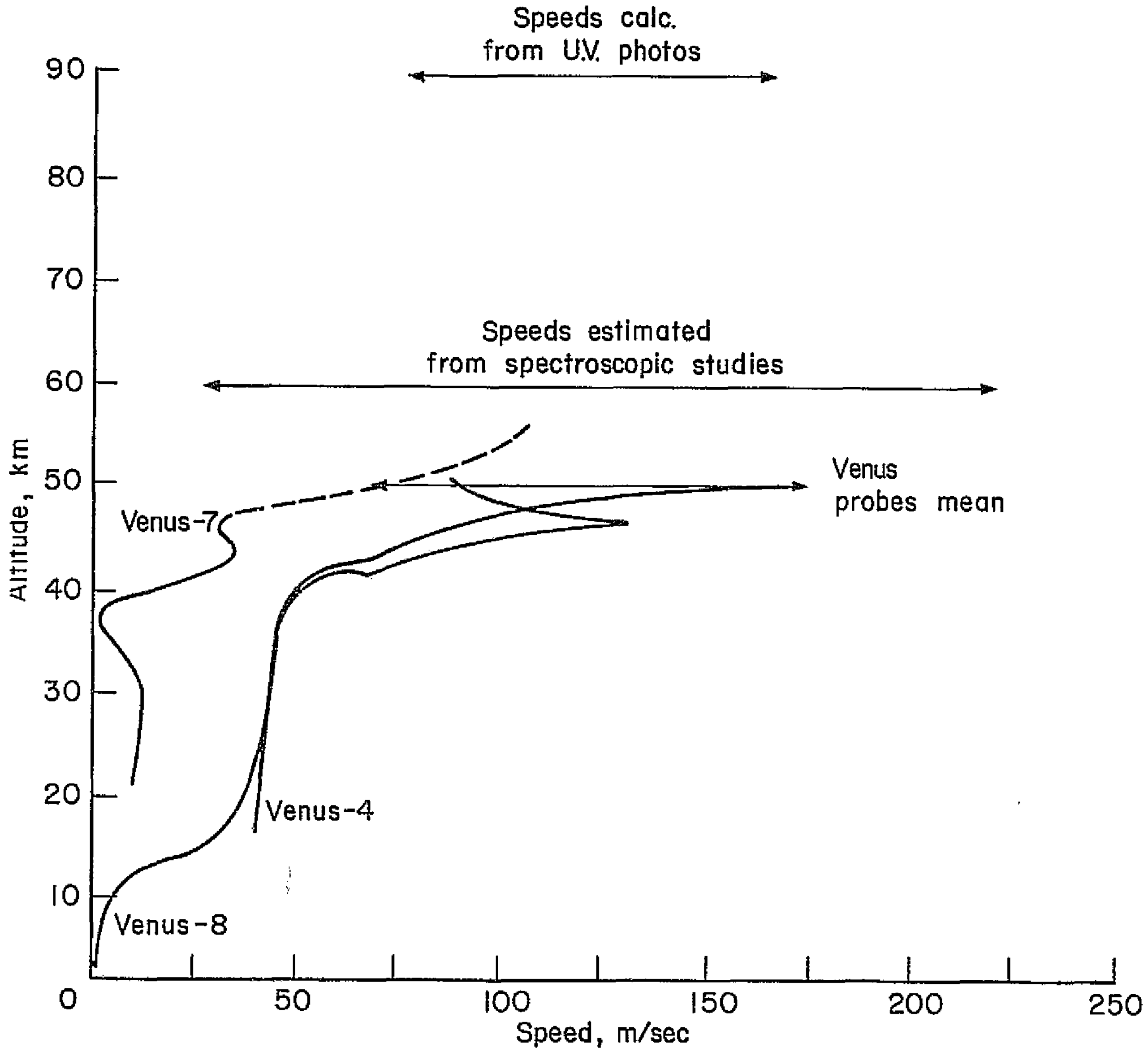

Figure 23.- Venera-4, -8 wind profiles.

inferred from the Russian spacecraft. There are regions, notably above 40 km and between 20 and 30 km, where the vertical velocities are surprisingly large, ~5 m/sec. The large vertical velocities above 40 km occur in the high-shear region of the zonal flow, a region where Mariners 5 and 10 both indicate a zone of turbulence (ref. 74). The large updrafts between 20 and 25 km appear to be correlated with a region in the atmosphere where the lapse rate becomes super-adiabatic (fig. 24) (ref. 21). Small-scale convection is also indicated in the region surrounding the subsolar point (ref. 69).

Horizontal temperature contrasts in the atmosphere are quite small, on the order of only a few degrees at an altitude of ~60 km (refs. 75 and 76). In the lower atmosphere, small temperature contrasts can be understood on the basis of the large thermal inertia and large-scale circulation, while in the upper atmosphere, where thermal time constants are on the order of a Venusian solar day or less, small temperature variations are due entirely to the large-scale circulation.

3.4 Clouds

When viewed in visible light, Venus is essentially featureless because of an almost uniform cloud cover extending from approximately 60-km altitude down to probably about 35 km. The composition and structure of these clouds have been investigated for many years; but only recently has a viable composition withstood comparison with most available experimental evidence. There is evidence for a number of cloud and haze layers extending ~20 km above the visible cloud deck, some of which are viewable only in the ultraviolet part of the spectrum (ref. 69).

Aside from interest in the clouds themselves, the determination of the composition and distribution of cloud materials in the atmosphere is important for at least two reasons. The horizontal and vertical distributions of solar heating, which drives the general circulation, and the thermal structure of the atmosphere are almost certainly determined to a large degree by the cloud material. Thus, an understanding of these phenomena is intimately involved with an understanding of the clouds.

There is considerable evidence at the present time that the visible clouds of Venus consist of a concentrated solution of sulfuric acid, approximately 75-85 percent H_2SO_4 by weight, which consists of particles about 1 μ/m in radius with concentrations of 10-100 cm^{-3} (refs. 52, 53, 57, and 77-80). Essentially, the evidence for sulfuric-acid clouds comes from determinations of the index of refraction and the infrared reflectivity as a function of wavelength, all of which measurements have been made from Earth, and which refer mostly to optical depth $\tau \lesssim 1$ (~70 km). There are indications that the clouds are at least partially sulfuric acid at greater optical depths (ref. 53); but whether cloud composition is a function of altitude is not known. Based on Venera-8 data (ref. 17) and the theoretical analysis of Lacis and Hansen (ref. 81), there are probably at least three cloud layers having different optical properties; but this may or may not imply compositional changes (figs. 25 and 26). The lower boundary of the clouds appears to be located at ~35-km altitude, as deduced from the abrupt change in the rate of decrease of downward solar

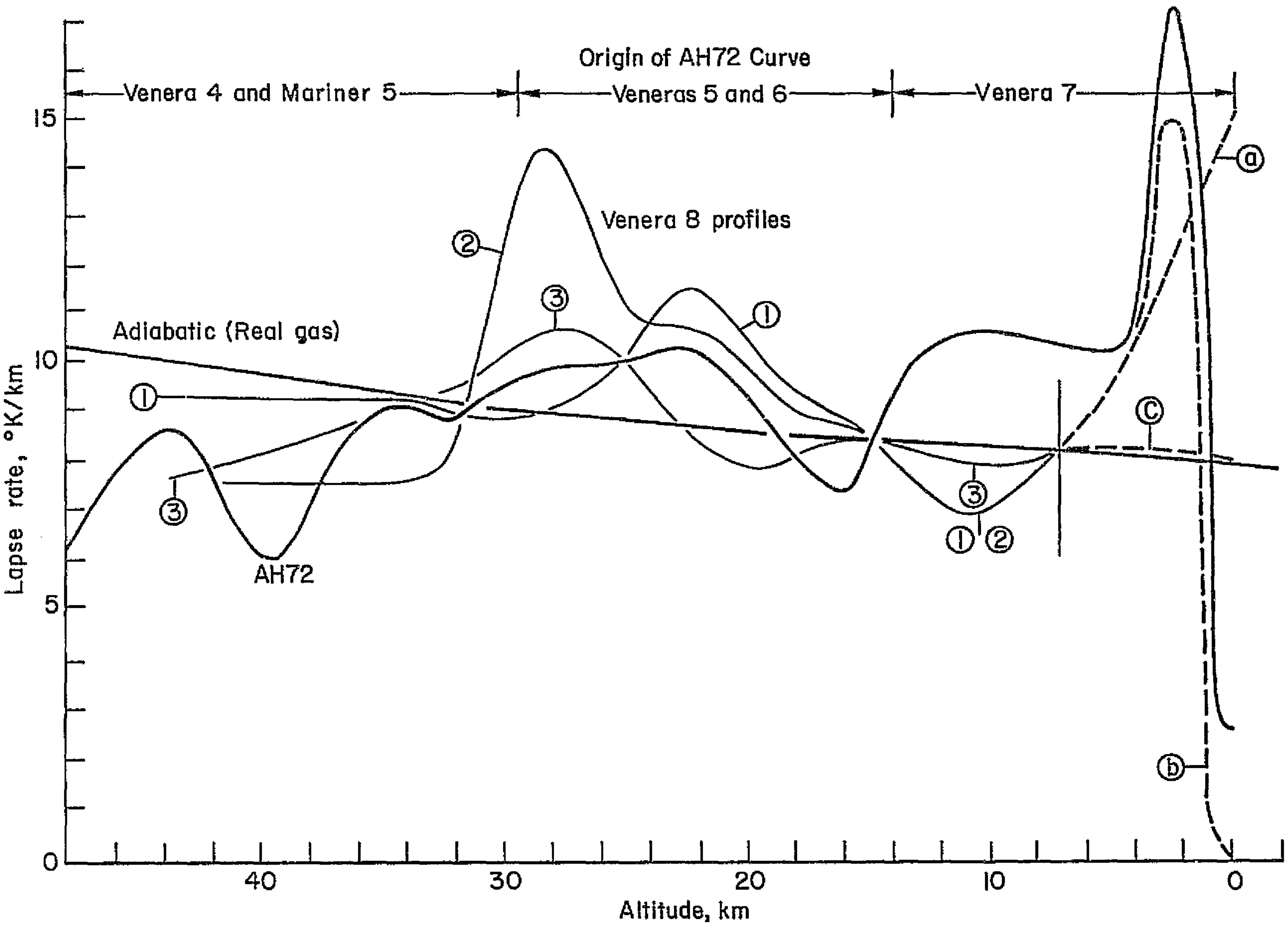

Figure 24.- The thick-line curves present the adiabatic lapse rate for the Venus atmosphere and the lapse-rate profile obtained by AH72 for the Mariner-5 and Venera-4, -5, -6, and -7 measurements. The thin-line curves are several possible Venera-8 lapse-rate profiles. The dashed-line curves indicate the wide range of lapse rates that are consistent with the uncertainty in interpreting the Venera-8 measurements near the surface.

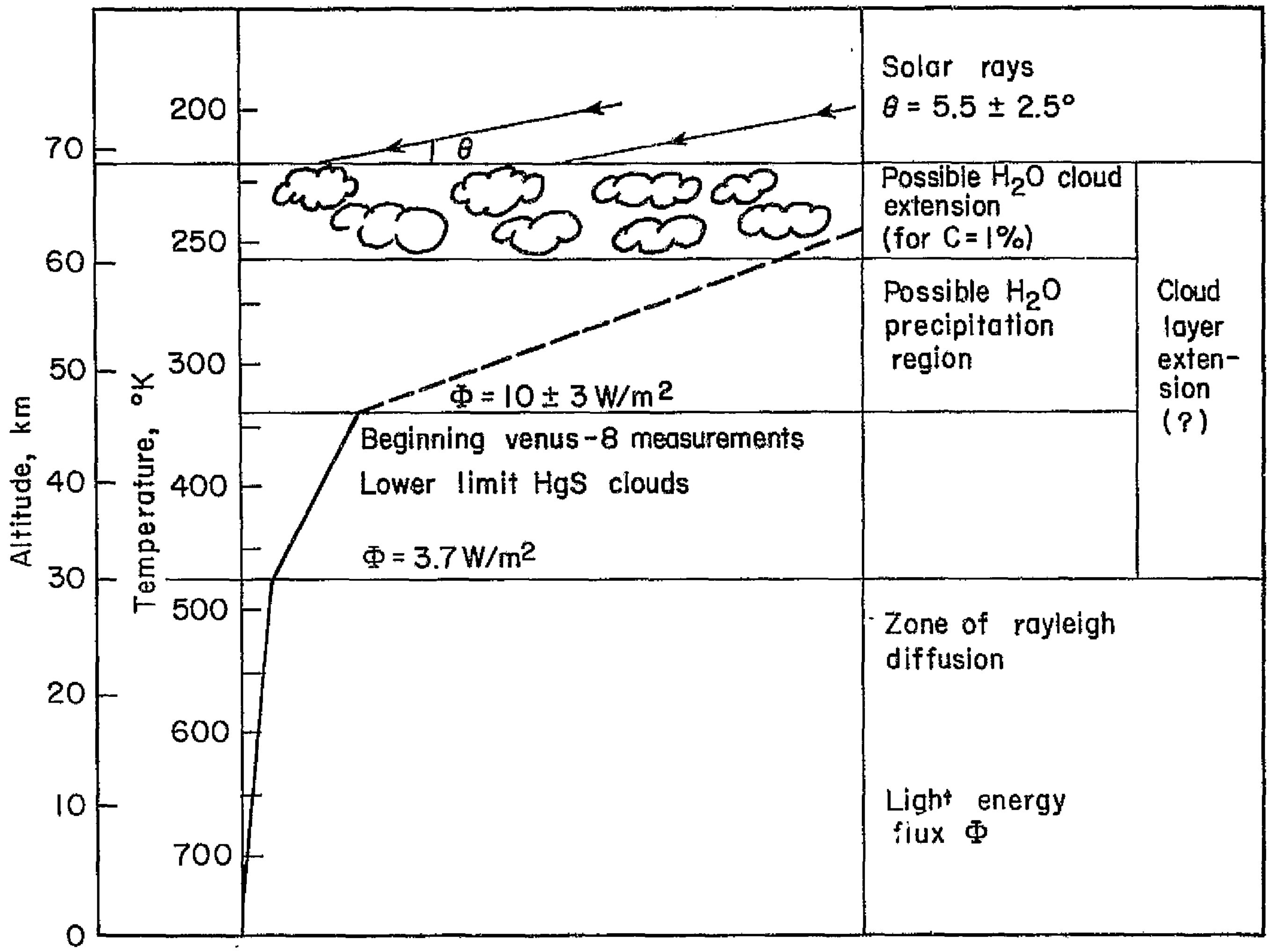

Figure 25.- Venera-8 light flux measurements (1)

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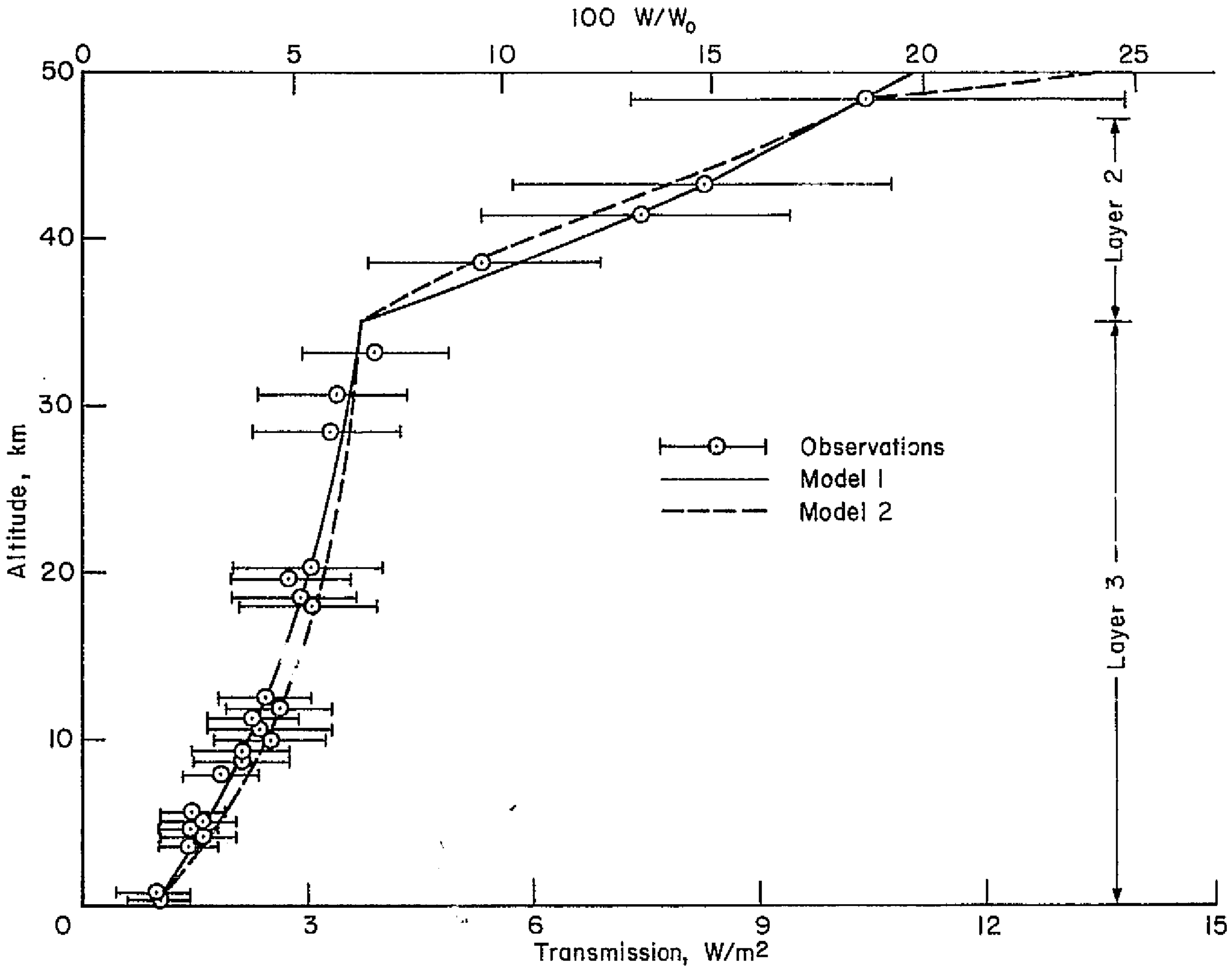

Figure 26.- Transmission of sunlight through the Venus atmosphere. The two theoretical curves are for two extreme models, with practically no absorption below 48.5 km (model 1) and all of the absorption below 48.5 km (model 2), compare table I. Both models have three layers with the boundaries at 35 and 48.5 km.

flux measured by Venera 8. Since Mariner 10 did not observe any shadows, the top of the visible cloud deck, located at approximately 60 km, is either (1) smooth, with height variations ≲ 100 m, (2) diffuse, or (3) located deep enough in the atmosphere that overlying clouds or hazes diffuse the sunlight enough at large zenith angles so that no shadows occur.

Above the visible cloud deck, Mariner 10 observed a number of highly stratified limb hazes at about the 10-mb pressure level (ref. 69), having vertical thickness of ~1 km. There appears to be some horizontal variation in these haze layers with a length scale of ~1000 km.

The nature of the UV features observed in Earth-based photographs and the imaging equipment aboard Mariner 10 is as yet undetermined. The observation that small-scale features change on time scales of a few hours suggests that the light and dark markings are due to some condensible substance (ref. 69), but the composition remains unknown as well as the processes causing the variations. The altitude associated with the features is presently uncertain, but probably lies between 60 and 80 km.

Concerning the energy balance of the Venusian atmosphere, which is influential in determining the circulation and thermal structure, we have at present little factual information. Given that the atmosphere is largely CO_2, and the Venera temperature profiles, one can construct models of the molecular absorption and emission of thermal radiation (optical depths >200) and the scattering and absorption of solar radiation. However, a serious gap is the quantitative description of the clouds that both scatter and absorb radiation at visible and thermal wavelengths. Therefore, the deposition altitudes of the solar radiation and the radiative exchange between the planet and the various levels of the atmosphere remain ill-defined. The Venera-8 measurements (ref. 82) in figures 25 and 26 show that the optical depth of the atmosphere near the morning terminator for solar radiation is about 8 in the visible spectrum. The bulk of the incident solar energy (0.96) was found to be absorbed or reflected at altitudes above the limit of the experiment (50 km at this large solar zenith angle), in confirmation of the major effect of clouds on the lower atmosphere energy balance. However, it has been estimated that as little as 1 percent of the solar energy is sufficient to maintain the lower-atmosphere temperature in the presence of the strong thermal blanketing greenhouse effect (ref. 83).

3.5 Surface and Interior

Because the surface of Venus appears to be completely obscured by clouds, conventional optical imaging systems cannot provide data for the surface. The current state of knowledge on surface morphology (craters, rough areas, elevated areas, linear features, etc.) is from Earth-based radar (e.g., Arecibo, Puerto Rico; Goldstone, California). These data are characterized (currently) by linear resolution on the order of 15-40 km at best, with coverage of parts of one side of the planet that faces Earth at every inferior conjunction. The radar data, in the form of reflectivities, do not completely distinguish between areas of enhanced backscatter gain due to increased surface roughness and areas of enhanced reflectivity due to increased dielectric constant

relative to some standard. Such a distinction is of obvious importance. Because resolution is strongly dependent on the distance to the target (to the fourth power), obviously there will be a practical limit to the resolution of all Earth-based systems.

Results from current studies (e.g., refs. 84-86) show interesting features. There are large-scale, regional differences in elevation on the order of 6 km. Compared to Earth, this is an appreciable relief. Less than 10 percent of the surface of the Earth has relief more than 6 km, and Earth, compared to the Moon or Mars, is a very active planet in terms of crustal tectonics and volcanism.

On a global scale (at least as seen by Earth-based systems), some of the Venusian relief can be related to specific landforms. A ridgelike mountainous area oriented roughly north-south has been observed to be about 6000 km long by 500 km wide and about 3 km high (ref. 84). In transverse cross section, it appears to be asymmetric, with a steeper, "scarp-like" slope of about 1/2° on its eastern side. The presence of this elevated region suggests some intriguing possibilities. The Tharsis Ridge of Mars, for example, is of comparable size, and it is the axis for the major shield volcanoes on Mars. Terrestrially, some large ridgelike regions are associated with colliding crustal plates.

A narrow linear feature ~300 km long, whose width is at or below the system resolution limit (~15 km), was recently described (ref. 86). Such a feature could represent a scarp indicative of faulting.

Earth-based radar has also revealed cratered terrains on Venus. The feature "alpha," for example, is a hugh circular feature more than 1000 km in diameter (ref. 85), in the same size class as the large lunar basins such as Imbrium and Orientale, and the Martian circular basin Hellas. Also present on Venus are many smaller circular depressions. One 1500-km circular area was examined by Earth-based radar in 1972 (ref. 86); it was found to be relatively level, but the data clearly showed features that appear to be rimmed craters 35-160 km in diameter with level floors. In addition, Saunders et al. (ref. 87) observed a distinctly rimmed crater 220 km in diameter. Large craters and basins on the Moon and Mars are considered to be impacts from an early period in the planet's history. If "alpha" and other large (>100 km) circular features are of similar origin, then these may represent old surfaces preserved since near the time of planetary formation. This, in turn, implies that at least parts of the Venusian crust have been modified little by internal processes and that surface processes have not been sufficient to completely degrade the old features. Very few large impact scars are preserved on the Earth because of the mobile crustal plates that are constantly forming and being subducted ("recycling" of the crust). In addition, the atmosphere and oceans have caused substantial erosion and deposition on Earth's surface. The presence of large craters (or at least suspected craters) on Venus suggests that the crust is not undergoing deformation, at least not like that on Earth, and that there may not have been primordial oceans on Venus, at least in the cratered areas. Alternatively, the Venusian craters could be young, either of internal origin or impact origin. It would seem unlikely that such large impacts would have formed late in the geologic history of Venus without similar impact craters being observed on Earth or the Moon.

Recently acquired interferometric radar maps with ~40-km resolution made using the Goldstone facility (Goldstein, personal communication, 1975) reveal still other surface features, including "chaotic" terrain, other rimmed craters, a hugh north-south canyon system perhaps comparable to the Martian Valles Marineris, and a linear rille-like feature more than 600 km long that appears to consist of connected circular elements, and one extremely bright region essentially unresolved (< 40 km in size).

The current state of knowledge of the nature of the near subsurface may be briefly stated. Direct measurements of some of the chemical properties of the subsurface material by gamma-ray spectroscopy was obtained by Venera 8 (ref. 88). The results give percent by weight of several natural radioactive elements: potassium ~4 percent, uranium $\sim 2 \times 10^{-4}$ percent, thorium $\sim 7 \times 10^{-4}$ percent. These amounts represent distinct enrichment over terrestrial mantle material, and they strongly indicate that differentiation has occurred, and, at least at the Venera 8 location, has manifested itself in a surface composition similar to that of granite, but with a soil of pumice-like density (ρ = 1.5 gm/cm^3).

The other piece of knowledge comes from a systematic study of combined radar/radio-emission data from Earth-based observations and various spacecraft atmospheric observations. A simultaneous fit of all these data to a comprehensive parametric model gives a subsurface dielectric constant of ~3.7 ±0.3, significantly higher than that of the Moon (~2.2), Mars (~2.5), or Mercury (~2.4). The model quoted (ref. 89) is not yet definitive in the sense that the dielectric constant is still a bit low to match radar observations for typical low-roughness surfaces such as we believe Venus to have. However, it does indicate that something is very different about the Venus subsurface: perhaps composition, perhaps density/porosity.

Many constraints on a planet's internal structure and composition are derived from its geometrical and gravitational figures. The mean density, which compositional models must conform to, is determined by the mass and radius. Low-order gravitational harmonics put constraints on the radial distribution of mass within the planet, if the forces giving rise to the distortion from sphericity are known. An offset of the center of mass from the center of figure, such as reported by Smith et al. (ref. 90), suggests differentiation under the influence of a global asymmetry. A mean density of 5.25 ±0.05 gm cm^{-3} has been inferred. The degree to which higher-order gravitational harmonics are present is indicative of the extent of lateral density inhomogeneities. This also bears on the problem of planetary differentiation. Correlation of topographic features with gravitational features can yield information on the processes responsible for both, as in the case of the lunar mascons.

Gravitational data are obtained by accurate determination of the actual spacecraft orbit by Doppler tracking, and the subtraction of effects not due to planetary gravity, such as radiation pressure, solar gravity, spacecraft outgassing, and atmospheric drag (ref. 91). The direction of the axis of rotation can also be determined from the spacecraft orbit.

Present knowledge of the gravity and shape of Venus is limited to accurate measurements of its mass (4.88×10^{27} gm) and radius (6050 ±0.05 km) by Mariner and Venera spacecraft, and by ground-based radar; a tentative upper limit to the fractional difference in the principal equatorial moments of inertia of 10^{-4} (ref. 28); the establishment of the existence of relief on a "continental" scale of the order of a few kilometers, and smaller scale features (basins, craters, and ridges) by ground-based radar, as described above; and the determination of an offset of the center of mass from the center of figure of about 1 km (ref. 90). The rotation period has also been established by ground-based radar to be very close to 243.16 days, a period corresponding closely to an Earth-oriented resonance. This is significant because theory seems to demand a fractional difference in the equatorial principal moments of inertia equal to or greater than the upper limit quoted above (ref. 92).

At present, we have no information regarding the general "smoothness" or "roughness" of the Venusian gravity field. Mars is apparently rougher than both the Moon and the Earth (ref. 93), thereby posing problems for any scheme that supposes a simple relation between gravitational roughness and planetary size.

The facts that (1) Venus is similar to the Earth in size and mass, (2) there is large-scale topographic relief, which, if compensated, implies the existence of large areas of differing average density, and (3) there is an offset of the center of mass from the center of figure suggest that Venus is a differentiated planet, perhaps possessing a mantle and an iron-rich core. This is supported by the fact that, in at least one location, there are rocks bearing granite-like radioactive-element concentrations. This is the extent of our present knowledge of the Venusian interior.

4.0 PIONEER VENUS AND FUTURE GROUND-BASED CONTRIBUTIONS

Following the outline of section 3.0, we summarize the expected contributions to knowledge about Venus from the Pioneer Venus Orbiter and Multiprobe Missions and from anticipated Earth-based radar and optical studies. The Pioneer Venus missions are described in appendix A and in section 1.3.2. The reader is particularly alerted to tables X, XI, and XII for scientific payload lists and to figures 4 and 5 for planetary coverage considerations. For quick reference, instrument acronyms used below are tabulated in table XX. Finally, table XXI summarizes the regions addressed in major and minor ways by each of the Pioneer Venus instruments.

4.1 Solar-Wind/Planet Interaction

Three instruments on the Pioneer Venus Orbiter are specifically appropriate to measurements in the interaction region: the plasma analyzer (OPA), the magnetometer (OMAG), and the electric field detector (OEFD). In addition, both the Bus (BIMS) and Orbiter (OIMS) ion mass spectrometers, retarding potential analyzer (ORPA), electron temperature probe (OETP), and radio-occultation experiment (OOCC) may make important contributions. An

TABLE XX.- PIONEER VENUS INSTRUMENT ACRONYMS

Orbiter	
ONMS	Neutral mass spectrometer
OIMS	Ion mass spectrometer
ORPA	Retarding potential analyzer
OETP	Electron temperature probe
OUVS	Ultraviolet spectrometer
OIR	Infrared radiometer
OCPP	Cloud photopolarimeter/imager
OPA	Plasma analyzer
OMAG	Magnetometer
OEFD	Electric field detector
ORAD	Radar mapper
OOCC	Radio occultation
ORS	Radio science
Multiprobe	
Bus	
BNMS	Neutral mass spectrometer
BIMS	Ion mass spectrometer
Large/small probe	
LNMS	Neutral mass spectrometer
LGC	Gas chromatograph
LCPS	Cloud particle size spectrometer
LN/SN	Nephelometer
LAS/SAS	Comparative atmosphere structure
SNFR	Net flux radiometer
LIR	Infrared radiometer
LSFR	Solar flux radiometer
DVLBI	Differential very long baseline interferometry
PRS	Radio science

TABLE XXI.- PIONEER VENUS EXPERIMENT REGIMES

Acronym	Solar-wind/ plant inter.	Ionosphere	Atmosphere Comp.	Atmosphere Str.	Atmosphere Dyn.	Clouds	Surface & interior
ONMS			XX	XX			
OIMS	X	XX					
ORPA	X	XX		X			
OETP	X	XX		X			
OUVS			XX	XX	X	XX	
OIR				XX	X	XX	
OCPP					XX	XX	
OPA	XX						
OMAG	XX	X					
OEFD	XX	X					
ORAD							XX
OOCC	X	XX		XX	X	X	
ORS				XX			XX
BNMS			XX	XX			
BIMS	X	XX					
LNMS			XX			X	
LGC			XX			X	
LCPS						XX	
LN/SN						XX	
LAS/SAS				XX	XX	X	X
SNFR				X	X	XX	
LIR				X	X	XX	
LSFR				X	X	XX	
DVLBI					XX		
PRS					XX		

unfortunate circumstance is that the orbital parameters, chosen on the basis of ionospheric in-situ instrument sampling requirements (section 4.2) and cloud-top polarimetric and imaging requirements (section 4.4), compromise the bow-shock and ionopause coverage for the OPA, OMAG, and OEFD. The expected coverage is illustrated in figure 27. Note the significant gap in coverage from 1.3 to 8 Venus radii.

The OPA will measure specifically solar-wind bulk velocity, flow direction, flux, and temperature. The instrument is sensitive to the following energy ranges: positive ions 50-8000 eV and electrons 0-250 eV. Within the thermal ionosphere plasma, the instrument has limited capability. The OMAG has two commandable dynamic ranges, $\pm 25\gamma$ and $\pm 50\gamma$, with resolutions of $\pm 0.1\gamma$ and $\pm 0.2\gamma$, respectively, and it should be particularly effective at tracing the transition from the freestream solar wind across the bow shock, ionopause, and ionosphere within the coverage constraints mentioned. The OEFD will provide significant information on the mode of plasma interactions between the solar wind and ionospheric plasma, the variable locations of the bow shock, ionopause, and wake cavity boundary, the role of plasma instabilities in modifying the heat flux from the solar wind to the ionosphere, the wave-particle interaction mechanisms that can cause "pickup" or thermalization of upstream ions formed when atoms from the exosphere are ionized in the streaming solar wind, and the extent of the upstream turbulence region. Wave-amplitude measurements will be made in four bandpass channels centered at 160 Hz, 730 Hz, 5.4 KHz, and 30 KHz (±15 or ±30 percent fractional bandwidth). The dynamic range of the instrument includes 50 μV/m to 500 mV/m. The ion mass spectrometers (BIMS, OIMS) and retarding potential analyzer (ORPA) will measure ion concentration and temperature and should be effective in defining the ionopause location. The electron temperature probe (OETP) will not only provide valuable ionopause location data, but also should shed very important light on the effect of solar-wind heating of the ionospheric plasma. Finally, the radio-occultation experiment will provide similar data to that of Mariners 5 and 10 on the ionopause structure.

It is obvious that no other experimental observations of the solar-wind interaction region will be made before Pioneer Venus, with the possible exception of Soviet attempts.

4.2 Ionosphere

There are three in-situ measuring instruments on the orbiter (ion mass spectrometer (OIMS), retarding potential analyzer (ORPA), electron temperature probe (OETP)), and there is one on the bus (ion mass spectrometer (BIMS)) to measure specific ionospheric parameters. The radio-occultation experiment (OOCC) is also of critical importance. Both the magnetometer (OMAG) and the electric field detector (OEFD) may provide interesting auxiliary data.

The OIMS and BIMS will perform exploratory in-situ measurements of the distribution and concentration of ionic constituents. Sixteen ion masses will be explored: 1, 2, 4, 8, 12, 14, 15, 16, 18, 24, 28, 30, 32, 40, 44, and 56 AMU. Emphasis will be given to the altitude range from 150 km (periapsis) to 5000 km for the orbiter and from ~135 km (bus-burnup) to several

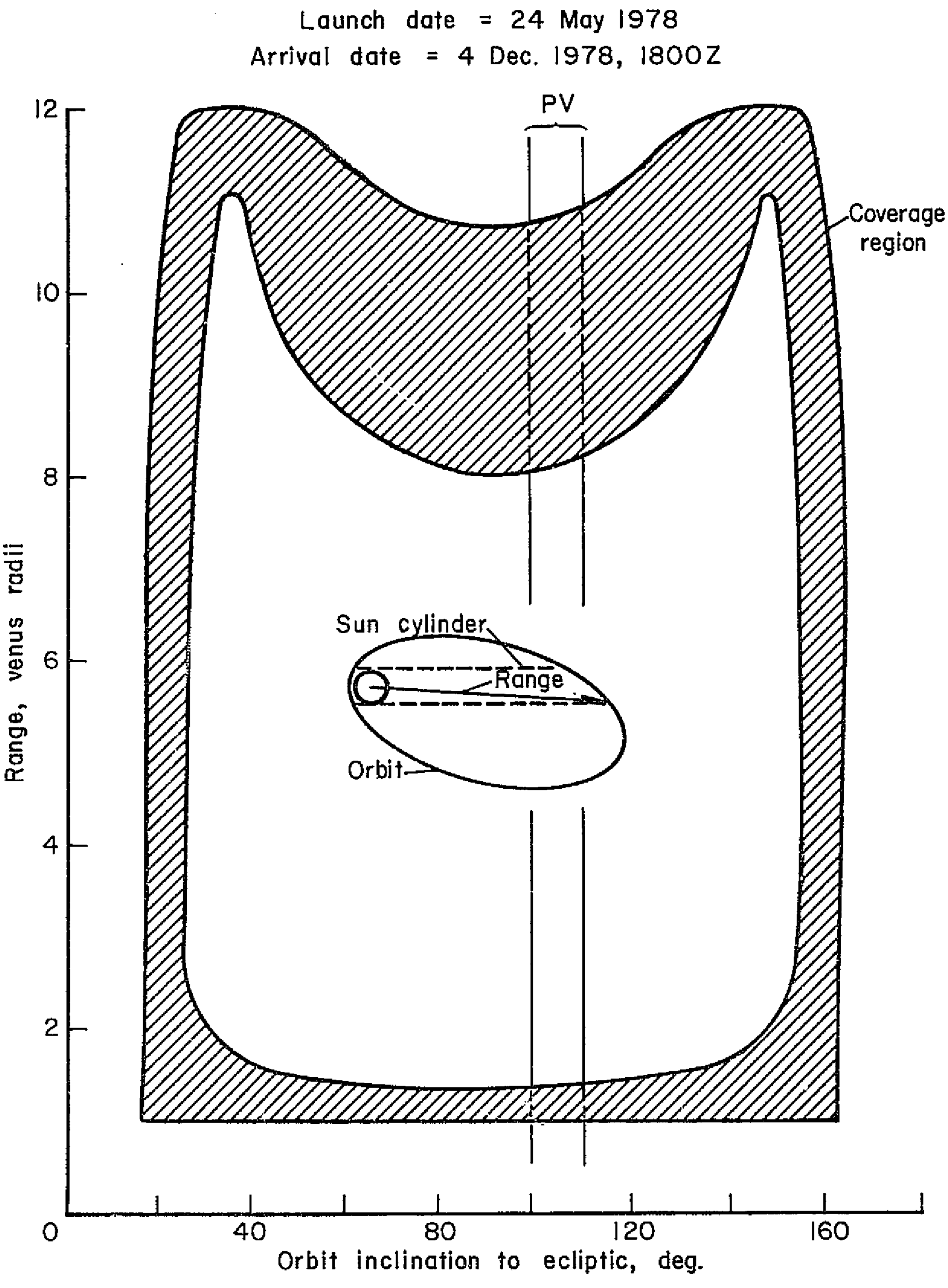

Figure 27.- Pioneer Venus solar-wind interaction coverage.

planetary radii for the bus. Note that whereas the orbiter will not quite make it to the Mariner-determined ionospheric peak (142 km), the bus should. The ORPA, in the same region as that of OIMS, will measure temperatures and concentrations of the most abundant ions, ion drift velocity, electron concentration and temperature, and the energy distribution function of ambient photoelectrons. These data should help determine the main sources of energy input to the ionosphere and the dominant plasma transport processes. The OETP will also provide critically required information on these processes. The major parameters measured are electron temperature and concentration, ion concentration, and mean ion mass. The OOCC experiment will provide electron concentration profiles (of course, not at the same locations as the in-situ measurements) throughout the ionosphere. Again, because of the chosen orbital parameters, these profiles will be limited mostly to the night-time hemisphere with possibly a few measurements on the dayside at very high latitudes only.

Note that the neutral mass spectrometers (BNMS, ONMS), the electric field detector (OEFD), and the magnetometer (OMAG) will provide additional data critical to the interpretation of the in-situ data and for ionospheric modeling purposes. Earth-based techniques for observations of the Venus ionosphere are nonexistent.

4.3 Atmosphere

4.3.1 Composition - The two neutral mass spectrometers on the bus (BNMS) and orbiter (ONMS) are the major upper-atmosphere composition in-situ sampling devices on the mission. In addition, the ultraviolet spectrometer (OUVS) will provide valuable composition data.

The BNMS will measure the number densities of the various atmospheric constituents and their altitude dependence from the instrument threshold altitude down to ~135 km. The mass range 1-46 AMU will be explored. The ONMS will make similar measurements of the same mass range from periapsis (150 km) to the sensitivity threshold altitude. Whereas the BNMS measurements will provide a single accurate altitude profile, the ONMS will provide vertical and horizontal variations with large coverage in longitude and latitude. The remote sounding OUVS will make spectroscopic measurements of the day and night airglow spectrum of Venus between 1100 and 3400 Å. In addition, limb profiles of selected airglow emissions will be made including OI 1304 Å, 1356 Å, 2972 Å; CI 1657 Å; HI 1216 Å; CO Fourth Positive and Cameron bands; CO_2^+ doublet bands. The intensity and distribution of the hydrogen Lyman-alpha corona will also be studied.

The composition of the lower atmosphere will be measured by the mass spectrometer (LNMS) and the gas chromatograph (LGC), both from the large probe only.

The LNMS will make approximately 60 mass sweeps over the range 1-208 AMU from parachute deployment (~67 km) to the surface. This mass range is sufficient to cover the expected gaseous compounds and, assuming the clouds are formed from condensibles, the vapors responsible will be determined. Note that

the composition of particulate-type clouds cannot be determined. Also, H_2SO_4 cannot be directly and uniquely measured, although gaseous compounds fractionated therefrom may be measurable. Isotopic ratios of He, Ne, Ar, Kr, and Xe will be specifically sought. Three samples will be taken to measure the atmospheric composition by the LGC. The following constituents will be specifically sought: Ne, H_2, N_2, O_2, Ar, CO, Kr, CH_4, CO_2, NH_3, COS, H_2S, SO_2, H_2O, C_2H_6, and HCl. The combination of ONMS, BNMS, LNMS, and LGC may permit reasonable determination of the turbopause altitude. However, for a discussion of the limitations in these measurements see sections 5.0 and 7.0.

Continued ground-based observations in the next four years may shed additional light on the composition above and near the cloud tops. Also, further analysis of the Mariner-10 ultraviolet-spectrometer data may also provide some valuable results. However, it is clear that the major contribution to atmospheric composition will come from Pioneer Venus.

4.3.2 Structure - The major contributions by Pioneer Venus to the structure and thermal balance of the upper atmosphere will be provided by mass spectrometers on the bus (BNMS) and orbiter (ONMS), the accelerometer determinations of LAS and SAS, the ultraviolet spectrometer (OUVS), the infrared spectrometer (OIR), the atmospheric drag radio-science experiment (ORS), the electron temperature probe (OETP), and the retarding potential analyzer (ORPA).

The BNMS and ONMS in-situ measurements provide spatial distributions of atmospheric composition. The height gradients (i.e., scale heights) inferred therefrom yield, unambiguously, altitude profiles of gas temperature. The OUVS and OIR remote limb sounders will also provide gas temperature profiles at locations and altitudes different from the in-situ devices. The radio science experiment (ORS) associated with spacecraft drag-induced orbital perturbations will provide a thermospheric density and temperature near periapsis (~150 km). Finally, the OETP and ORPA will provide in-situ direct measurements of electron and ion temperature profiles from about 150 to 5000-km altitude.

The major structure observations in the lower atmosphere will be made by the comparative atmospheric structure experiments on each of the small (SAS) and large probes (LAS) and the radio-occultation experiment (OOCC). Thermal balance observations will be made by the net flux radiometers on the large probes (LSFR, LIR) and the small probes (SNFR).

The LAS and SAS experiments define the atmospheric temperature and pressure profiles along the probe descent path. The temperature and pressure observations will be made by direct sensing from about 67 km to the surface, while the same parameters will be derived from acceleration measurements at higher altitudes extending to about 200 km. The radio-occultation experiment (OOCC) will provide refractivity, thus p-T profiles, down to the critical refraction level (~35 km). The radiometers (LSFR, LIR, SNFR) will map the sources and sinks of opacity to solar visible and planetary thermal radiation. These measurements, in conjunction with the SAS and LAS experiments, should provide extensive data on the thermal structure and insight into the circulation driving forces of the Venusian lower atmosphere.

4.3.3 Dynamics - Winds and planetary-scale circulation in the lower atmosphere will be measured primarily by ground-based Doppler and interferometric tracking measurements of the individual entry probes (DVLBI, PRS). Smaller-scale turbulence observations will be detectable in the radio-occultation experiments (OOCC), the accelerometer data of LAS and SAS as well as the PRS observations. Data related to the driving mechanisms for the circulation patterns will be obtained from the atmospheric structure experiment (LAS, SAS) and the net-flux radiometer experiments (LSFR, LIR, SNFR). Horizontal motions near the cloud tops will be determined primarily from the cloud-imaging experiment (OCPP) and, secondarily, by the other orbiter optical experiments (OUVS, OIR), although the radio data (PRS, DVLBI) may be extended into the region above the clouds with suitable analysis of the entry probe dynamic response to the winds (DVLBI, LAS/SAS).

4.4 Clouds

The primary experiments for measuring cloud properties are the cloud particle-size spectrometer (LCPS) on the large probe and the nephelometer experiments on the large (LN) and small (SN) probes. Important cloud-top observations will also be made by the orbiter optical experiments (OCPP, OUVS, OIR). Other contributions to cloud knowledge will be made by the radio-occultation experiment (OOCC), the atmospheric structure experiment (SAS/LAS), and the net-flux radiometers (LSFR, LIR, SNFR). As discussed above, the composition experiments (LNMS, LGC) will contribute to cloud condensible knowledge.

The LCPS experiment is proposed to measure the particle size and number density in the clouds and lower atmosphere of Venus in the size range 0.3-500 μm (see sections 5.0 and 7.0 for further discussion). The measurements will be made below 67 km to the surface on the large probe only and will resolve individual cloud levels to ±500 m. Specific information as to mean particle size and mass, along with integrated cloud parameters such as mass content, optical depth, and size spectral properties will provide clues to basic formation processes and other thermal-radiative interactions. The LN and SN will explore the vertical structure of the clouds to a resolution of ~300 m and will provide evidence for the existence of solid or liquid particulates from about 67 km to the surface. Vertical stratification variations with latitude and longitude will be deduced from all the probes. The principal objectives of the OCPP experiment are to determine the vertical distribution of cloud and haze particles in and above the visible clouds for many locations on the planet, and to observe the ultraviolet markings and circulation patterns and measure the apparent cloud motions on time scales from ~15 min to the length of the mission (243 days). The instrument has three operating modes:

(a) Photopolarimetry - intensity, degree of polarization, direction of vibration for four spectral bands (2550-2850 Å, 3500-3800 Å, 5450-5550 Å, 9450-9550 Å) with a 7 × 9 mrad field of view

(b) Imaging - intensity of UV spectral band (3000-3900 Å) with a 0.4 × 0.5 mrad field of view (30-km resolution at subsatellite point); requires ~3.5 hr/full image

(c) Periapsis limb-scan intensity for a visual passband (5000 to 8000 Å) with 0.25 × 0.25 mrad field of view (resolution 0.5-1.0 km)

The OUVS will measure the UV scattering by the cloud tops, hazes, and adjacent atmosphere and investigate the spectral nature, distribution, and movement of the UV albedo features. The UV spectral features may provide clues as to the absorber responsible for the Mariner-10 UV markings. The spectral soundings will be made in the 1900-3400-Å band (overlapping the OCPP images). Disk scans of the backscattered sunlight will also be made at selected wavelengths. The OIR will measure the net Bond albedo (0.2-5.0 μm) for Venus and will study the morphology and spectral properties of the uppermost cloud layers and their global variability. The latter will be addressed by the simultaneous application of five approaches:

(a) thermal mapping in an atmospheric window

(b) temperature sounding measurements in adjacent fields of view

(c) temperature sounding measurements at the same point from different zenith angles

(d) spectral albedo measurements to map high clouds

(e) limb scans in the near, intermediate, and far infrared

As described previously, vertical cloud-structure data will be provided by the OOCC, LAS/SAS, LSFR, LIR, and SNFR, the latter three instruments providing, in addition, critical data on the cloud optical/radiative properties. Although the LNMS and LGC may provide data on cloud condensible chemistry, there is a disturbing possibility that good cloud-composition measurements may not result.

The recent accumulation of ground-based polarimetric and spectroscopic data on cloud-top properties has spurred the establishment of future, pre-Pioneer Venus coordinated ground-based observations. These should provide interesting data; however, more definitive answers must await Pioneer Venus.

4.5 Surface and Interior

Clearly, the surface and interior are the least known aspects of Venus. Unfortunately, Pioneer Venus will provide limited additional knowledge; in fact, ground-based radar observations from the Goldstone, Haystack, and Arecibo observatories will provide most of what we know about the Venus surface for the foreseeable future. On the other hand, Pioneer Venus will provide some appetite-whetting information. Surface data will be provided by the radar mapper (ORAD), and interior data by the orbiter Doppler tracking experiments (ORS).

ORAD will make the following observations:

(a) absolute surface heights along the suborbital track to an accuracy of about 100 m or better, and from these an estimate of global shape

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(b) dielectric constant and mean surface undulation (i.e., small-scale slopes) for areas lying along the suborbital track

(c) radar images of selected regions of the surface

The surface resolution of the ORAD in the altimetry mode varies with height; at 200 km, the surface resolution is 2 km along and 16 km across the suborbital track. The corresponding values at 1500-km altitude are 19 and 41 km, respectively, while at 3000 km they are 53 km in both directions. The accuracy with which the planetary radius of the resolved areas may be determined varies from less than 50 m at periapsis up to about 100 m at the upper-altitude limit of about 3000 km.

For the orbital inclination of 105°, the global topographic coverage will extend from about 30° south latitude up to the northern culmination limit of 75°. The density of coverage in longitude is set by the spacing of successive daily suborbital tracks and by the extent to which this experiment is operated. The planetary rotation yields a day-to-day track spacing at the equator of about 150 km, reducing to zero at 75° N.

Radar images consisting of about 50 pixels/image may be obtained below an altitude of about 500 km. Surface resolution varies from 20 to 40 km square depending on altitude. Images taken on successive spacecraft rotations will not overlap significantly, and will be centered between 70 and 150 km to one side of the suborbital track for altitudes between 150 and 500 km, respectively. The celestial mechanics experiments, using Doppler tracking of the orbiter to define the orbital elements and perturbations (ORS), should provide interesting data with regard to gravitational harmonics, Venus spin vector, and polar motion. Combined with the topographic data from ORAD, information about the internal density distribution and degree of compensation of surface features will be obtained. A background seismic noise experiment using the LAS/SAS accelerometer in a seismometry mode is also planned should any of the probes survive impact.

Earth-based radar measurements will undoubtedly continue to provide exciting results. In the near future, radar results will attain an improved resolution due to the resurfacing of the Arecibo telescope of typically 2 to 4 km over 25-50 percent of the hemisphere of the planet that faces the Earth every inferior conjunction. A projection of the radar coverage for Venus to be obtained in the 1975-1980 time period is shown in figure 28; however, the lower limit of 1-km resolution is now considered doubtful (F. Drake, D. Campbell, personal communication, 1975). Due to the strong dependence on Earth-Venus distance (R^{-4}), it is unlikely that Earth-based radar will obtain significant data for the other hemisphere, visible mainly near superior conjunction.

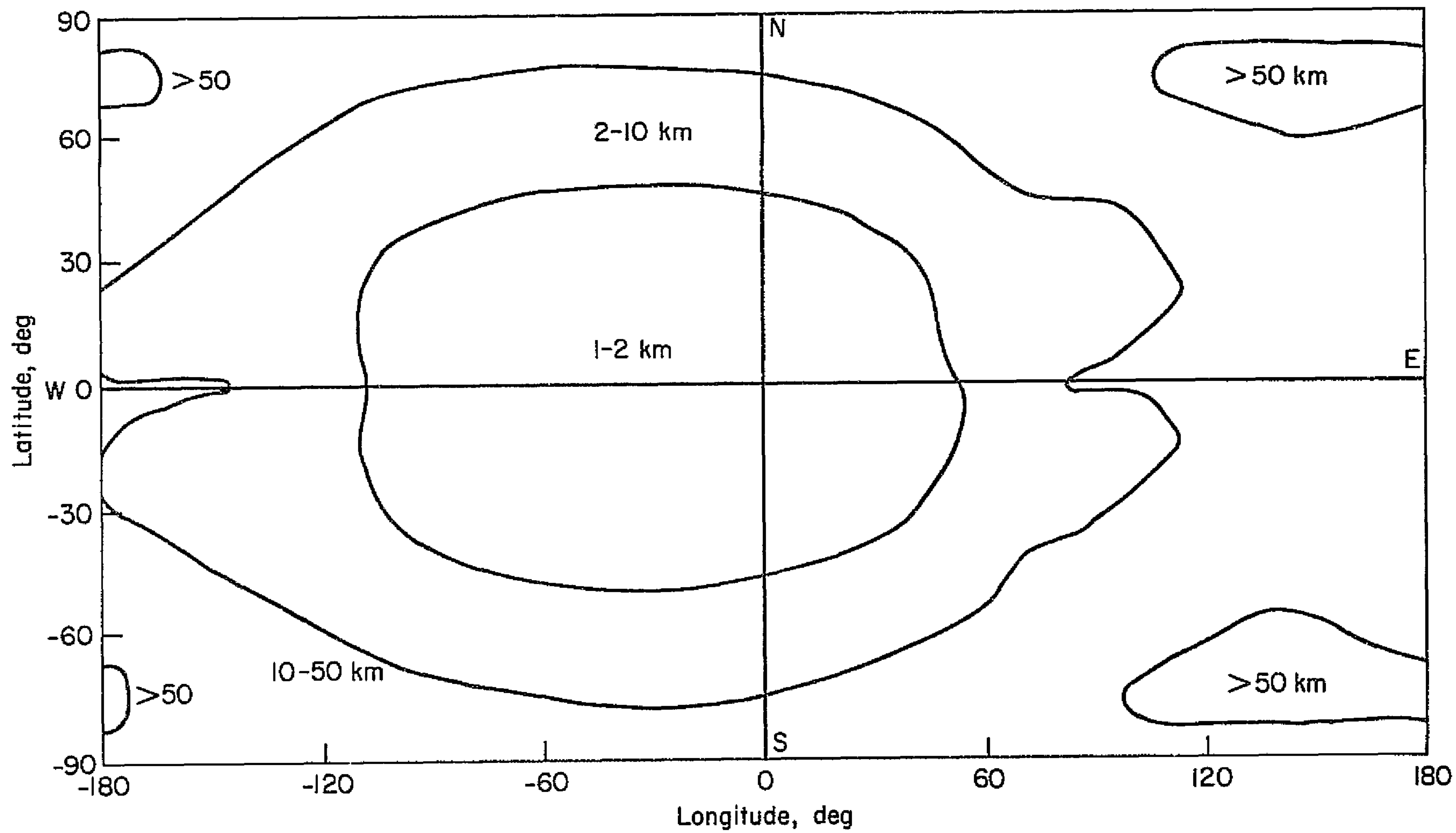

Figure 28.- Predicted Earth-based radar resolution of Venus - 1975, 1977, 1980.

5.0 POST-PIONEER VENUS KNOWLEDGE

In section 4.0 we have attempted to outline the means by which Pioneer Venus will attack many of the current scientific questions concerning Venus discussed in section 3.0. In this section, we deal with the task of assessing how well that attack will be made for the ultimate purpose of suggesting future missions to Venus. Two obvious constraints are placed on us. First, the assumption must be made that the Pioneer Venus missions will be 100 percent successful and that each instrument will work as planned. Given minor failures, however, hopefully there will be enough flexibility in future missions both to cover any resulting losses of data and to proceed logically with Venus exploration with a minimum of experiment repetition. Second, the history of exploration teaches us that missions often disclose new problems that were unanticipated. Pioneer Venus should prove no exception, but there is no way for us to anticipate now the new problems that may be identified. Both of these circumstances may suggest to some that planning for future missions should await completion of Pioneer Venus. This is not a desirable approach as it would preclude taking advantage of the highly desirable continuous sequence of launch opportunities available from the 19-month (584 days) synodic period. It does suggest an orderly set of prescribed missions with flexible, built-in contingency options.

Our approach to identifying the gaps in understanding Venus which will remain after 1979 is to summarize the things that Pioneer Venus (and Earth-based observations) cannot or will not accomplish. This analysis should not be taken out of context to conclude that we believe Pioneer Venus to be a planetary mission of limited scientific worth. This is definitely not the case. One need only peruse section 4.0 to be convinced of the outstanding contributions expected of the Pioneer Venus program.

As with any planetary mission, the limitations of Pioneer Venus occur in two areas: coverage and scientific instrumentation. The planetary coverage limitations are enumerated below:

(1) The multiprobe mission is limited to four lower-atmosphere probes (one large probe, three small probes) and one upper-atmosphere probe (bus).

(2) All probe targeting is limited to within about 60° of the sub-Earth point.

(3) Upper-atmosphere bus measurements are limited to above ~135 km (lower-altitude limit).

(4) Lower-atmosphere probe measurements are limited to below ~67 km (upper-altitude limit).

(5) Probes are not designed for survival at the surface.

(6) Orbiter parameters are such that experimental compromises are necessary.

The ramifications of these coverage limitations can be seen as follows. Having only four lower-atmosphere probes limits the resolution with which circulation and wind patterns may be determined. Also, it may well be impossible to map accurately the driving forces causing the observed circulation. Mariner 10 exposed both planetary-scale and smaller-scale dynamic features in the visible clouds; first-order new data on the former should be supplied by Pioneer Venus. However, if the probes penetrate some of the more local features, this may cause difficulty in interpretation of larger-scale motions. An important deficiency caused by the multiprobe targeting constraint is the inability to get near the subsolar point, the antisolar point, and a polar region. Mariner 10 data displayed some very interesting UV features in these regions, for example, bow waves and circumpolar jets, which may thus be unexplored by the Pioneer Venus probes. The multiprobe mission coverage gap between 67 and 135 km may or may not be serious. Important features, for example, the Mariner 10 UV markings and haze layers and probably the turbopause region, all lie in this gap. Although these phenomena can be modeled to some extent with the joint use of multiprobe (bus and large probe) and orbiter (remote sensing) data, in-situ exploration is lacking. The fact that probe survival is not required precludes the direct surface and interior observations possible from a survivable lander.

High-inclination orbiters with middle-latitude periapsis location are important for good global coverage of at least one hemisphere by the remote-sounding experiments, particularly those that operate in the nadir mode. On the other hand, certain experiments are thus compromised. For example, the solar-wake and upstream solar-wind observations become severely limited. Also, the radio-occultation observations are limited to mainly nightside sampling and at best to very-high-latitude dayside sampling. The low periapsis (150-km) orbiter is specifically required by the in-situ measuring instruments (although the peaks at 142 km in the ionospheric data from Mariners 5 and 10 will not be directly measured) and the atmospheric-density experiment may impose difficulties for the gravity-field determinations.

The scientific instrument limitations of Pioneer Venus are also important. The Pioneer Venus program is atmospherically oriented at the expense of surface and interior observations. The orbiter radar mapper will provide useful topographic data and some limited imaging capability. Its primary value as an initial imaging mission will be to provide some preliminary information on the surface region of Venus which cannot be studied from Earth in the near future, for example, high latitudes and the "backside" of the planet. An excellent global set of simultaneous in-situ measurements of the upper atmosphere and ionosphere will be made from the orbiter. Both the limitations of the solar-wind coverage and the absence of nonthermal particle detectors within the "magnetosphere" will possibly limit our full understanding of the precise nature of the solar-wind/ionosphere interaction.

A major experiment limitation associated with the multiprobe mission is the limited overall payload capability of the small probes. Unlike the large probe, the small probes will lack measurements of atmospheric composition and solar-flux deposition profiles. Thus, only the large-probe will measure atmospheric composition, cloud composition (if formed from condensibles), and

thermal balance. Horizontal variations of these factors can only be modelled, with the aid of the complementary measurements on the small probes. No direct measurements will be made of particulate or dust composition; if they are responsible for any cloud formations, then our understanding will be severely compromised. Another clearly important measurement will be lacking: a direct evaluation of the turbulent-mixing processes in the atmosphere, particularly as they relate to the now classic CO_2 stability enigma.

In addition to experiments which will not or cannot be made, there are definite limitations associated with several of the extant experiments. For example, the orbiter ultraviolet spectrometer experiment has a more limited useful wavelength range than desired, particularly with regard to observation of He-associated emissions. The orbiter cloud-imaging experiment will be limited by the relatively long imaging time required (~3.5 hr); short-term measurements of the dynamics of the UV cloud features will thus be compromised. Both the large probe cloud particle size spectrometer and the small probe and large probe nephelometers have limited capabilities at the highest altitudes (67 km) within the haze layers. Both experiments have relatively high thresholds to particle number density. Finally, the optical experiments on the large and small probes required for thermal balance studies may have extreme difficulty in maintaining sensitivity and accuracy operating in situ, as they must, in the hostile Venus environment.

The major deficiencies and constraints of Pioneer Venus in addressing the outstanding scientific questions associated with Venus were summarized above. These and other relatively minor problems are discussed in more detail in the following sections. New approaches and concepts are suggested to overcome or circumvent these deficiencies, and they provide the rationale for future spacecraft missions to Venus.

6.0 ORBITERS

From the discussions in sections 3.0 to 5.0, it is apparent that many scientific questions about Venus will remain unanswered in the post-Pioneer Venus period. In this section, we discuss experiments and research areas that can be approached best from orbiting spacecraft. A scientific rationale is developed first for the types of experiments and instruments proposed. All of the instruments are discussed briefly, with particular emphasis given to "new" orbiter instruments (e.g., the imaging radar). Engineering constraints on orbiter missions are also discussed and, lastly, recommendations are made for the priorities of experiments.

6.1 Science Rationale

Of all the types of missions discussed here, the orbiter is unique in that it can make useful observations of Venus from the solar-wind interaction region, through the ionosphere, atmosphere, and clouds all the way to the surface, and even can provide information concerning the interior. Thus, the approach

followed is to examine each of the major subject areas of Venus science given earlier and to consider gaps in knowledge which will remain after Pioneer Venus.

6.1.1 Ionosphere and solar-wind interaction - As discussed in sections 4.0 and 5.0 and appendix A, a significant fraction of the Pioneer Venus orbiter science payload and the multiprobe bus is dedicated to ionosphere and solar-wind interaction-region measurements. Even though an enormous amount of information will be collected, a few very important gaps in knowledge will remain. The major gap probably involves an incomplete mapping of the bow shock and ionopause boundaries resulting in incomplete knowledge concerning energy balance and transport across the boundaries, ionospheric heating effects, charge-exchange processes, and mass scavenging. The ionopause boundary could be mapped by a lightweight swept-frequency sounder of the type flown so successfully in the Earth-orbiting Alouette/ISIS program. The sounder would permit continuous determinations of electron density profiles and irregularities below the orbiter, and should map quite accurately the ionopause boundary and its variations with solar-wind conditions during the lifetime of the mission. Further, a low-energy particle detector would be highly desirable. The major requirement of an orbiter mission for ionosphere and solar-wind investigations will be the choice of an orbit configuration that permits high interest regions to be sampled. This is attested by the choice of periapsis altitude, apoapsis altitude, latitude of periapsis, and inclination.

With or without the addition of the above instruments to a Pioneer Venus payload, an orbiter mission flown during a sunspot minimum period (1983) would complement the Pioneer Venus sunspot maximum period. Clearly, a dedicated mission for this purpose can not now be justified; however, an ionosphere and solar-wind interaction experiment package on a radar imagery mission in 1983 (or even 1981) would be advantegeous.

6.1.2 Atmosphere and clouds - There are 19 experiments on the Pioneer Venus multiprobe and orbiter missions designed to measure neutral atmospheric properties associated with composition, structure, dynamics, and clouds (table XXI). If all the objectives of these experiments are met, a wealth of new information on the atmosphere will be obtained. This does not mean, however, that all major questions will be resolved. As discussed in section 5.0, some will remain due to limitations of the instruments, the observing geometry, and the entry locations. Furthermore, in addition to answering key questions, the mission very probably will disclose new questions not now perceived.

If we limit ourselves here to discussing presently identifiable limitations in the expected knowledge of the atmosphere to which future orbiters should respond, the following list is suggested: (1) resolution of the CO_2 stability problem, (2) vertical mass-transport rates, (3) broader global definition at good spatial and temporal resolution of the circulation patterns above the visible clouds, seen in the UV, (4) variation of upper-atmospheric neutral and charged species and temperatures over the solar cycle, (5) circulation in the upper atmosphere available to transport ions from the sunlit to the night side, (6) cloud composition, and (7) nature of the UV absorber responsible for the UV features observed by Mariner 10.

The CO_2 stability problem has resisted final resolution on the basis of previous space-flight missions, in which UV and radiometry have been the primary measurements, although final results are not yet in from the Mariner-10 flyby. That mission, in fact, suggests a much higher concentration of CO than was measured earlier, as much as an order of magnitude higher (ref. 40). Future orbiter missions should acquire data both by remote sensing (UV spectrometer) and by in-situ measurements (ion and neutral mass spectrometers), as will Pioneer Venus, and should be designed for periapsis as low in the atmosphere as is consistent with mission lifetime, preferably to 150 km or below, so that in-situ measurements can yield the maximum useful information. A question raised by the Mariner-10 UV spectrometer also requires resolution, the explanation of the large zeroth-order signal. Does this represent an unidentified major species or an instrument artifact?

Vertical mass transport is connected intimately with upper-atmospheric species distributions and chemistry. Orbiter techniques for determining species altitude profiles include both in-situ measurements and UV and IR spectrometry. In the latter case, modeling in which vertical transport may be a parameter is used to generate profiles to match the observations. Given the species profiles, further modeling involving production and loss mechanisms for individual species and vertical transport are invoked to deduce the transport rates. Another technique not previously available and which is somewhat more direct is to analyze data from the upper and lower atmospheres in combination for unreactive species such as helium, neon, and argon. These will be measured in the lower atmosphere by the Pioneer Venus mass spectrometer, but they will not be detected in the upper atmosphere by the Pioneer Venus UV spectrometer because of wavelength limitations (it does not see below 1100 Å). A future orbiter should therefore carry a UV instrument capable of working in the wavelength band down to 300 Å, in which these inert gases have resonance lines. The Pioneer Venus bus neutral mass spectrometer, however, should be able to detect these species, and useful modeling of vertical transport may result from comparisons with the lower-atmosphere values. A problem is the altitude gap from 65 to 135 km where no in-situ data are expected.

A similar limitation on the Pioneer Venus IR radiometer is its restriction to two broad-band channels (0.4 to 4 μm and 40 to 60 μm). An IR spectrometer capable of working from 0.4 to 60 μm would be valuable for future missions to detect specific infrared active molecules, including H_2O, while further investigating such properties as the vertical temperature profiles above the clouds and the cloud-surface temperatures.

Other improvements in the cloud observations from the orbiter would be desirable: one is increased vertical resolution of the photopolarimeter and the infrared radiometer. Currently, the photopolarimeter has a vertical resolution of approximately 1 km, and the infrared radiometer has a vertical resolution of at best 5 km. A vertical resolution of a fraction of a kilometer would be desirable, if possible, since the high-altitude hazes observed by Mariner 10 are about 1 km thick.

With respect to the circulation in and above the clouds (questions 3 and 5 above), the primary limitation of Mariner 10 was limited global and temporal

coverage. The spacecraft saw primarily one side of the planet, and its instruments did not record analyzable patterns at latitudes greater than about 50°. Pioneer Venus is expected to have improved global coverage, but it will require about 3.5 hr to image the full disk. In the presence of high cloud velocities, this could lead to distorted patterns and an inability to follow small-scale features of short lifetimes. Thus, on a future orbiter mission, an imaging system with higher speed (imaging times on the order of 10 min) and high spatial resolution (better than 100 km) could lead to much improved insights into the character of the motions and perhaps to a better understanding of the nature of the UV haze. Mariner 10 demonstrated such capability for an imager mounted on a stable platform, but the imaging rate from spinning spacecraft should also be improved for this and other future applications. Both wide-angle and narrow-angle capability should be included. Currently, study is being devoted to improving the imaging capability of spinning spacecraft at JPL in a study sponsored by Ames Research Center.

Thus, atmospheric measurements on future orbiters should include the following instruments: (1) a neutral mass spectrometer for in-situ measurements of the upper atmosphere; (2) a UV spectrometer for in-situ coverage from 300 to 3000 Å; (3) an imaging system to photograph the upper-atmosphere circulation patterns globally in the UV, with imaging times on the order of 10 min or less, and spatial resolution capable of resolving 100-km features; (4) an IR spectrometer with spectral coverage from 0.4 to 60 m; and (5) cloud photopolarimeter. These instruments, by extending the capabilities of those flown earlier or to be flown on Pioneer Venus, offer the possibility of resolving significant questions expected to remain after Pioneer Venus. They could make important contributions to our understanding of the atmosphere.

6.1.3 Surface - At best, Pioneer Venus and refined Earth-based radar data will answer only the very rudimentary questions about the surface of Venus, and questions regarding the present and past nature of the surface will remain unanswered. To obtain these answers, we must gain knowledge of (1) global morphology, (2) characteristics of craters, (3) distribution of rock units, and (4) nature of active processes on the surface.

6.1.3.1 Global morphology: Global morphology concerns the type and distribution of primary physiographic regions such as continents and basins. From our present knowledge of the physiography of the inner planets, all appear to be basically asymmetric. Although the reasons for the asymmetry are not clearly understood, the asymmetry seems to be related to the general evolution of the planetary crust and interior. Comparisons of physiography with gravity data for the Moon and Mars are providing clues to the nature and history of these planets and could be expected to provide similar clues for Venus. However, global gravity data and images at sufficient scales to permit these comparisons are required.

6.1.3.2 Crater analyses: Studies of crater morphology and crater frequency distributions have been an important means for determining the gross geologic history of the inner planets (see appendix C). While there are large uncertainties in the absolute age of surfaces derived from crater statistics, it is apparent that these data have provided much information on the nature

and history of geologic processes on the Moon, Mars, Mercury, Phobos, and Deimos.

Radiogenic ages for different lunar surfaces, obtained from returned samples, show that a heavy period of meteoroid bombardment occurred on the Moon in its first half billion years of history. The heaviest cratered terrains of the Moon and Mars reflect this early period of cratering. Soderblom et al. (ref. 94) have argued that since the oldest postaccretional mare-like surfaces on Mars and the Moon display about the same crater density, then the impact fluxes at Mars and the Moon have been about the same over the last 4 billion years. He has used the observed density of craters between 4 and 10 km in diameter, formed after the early rapid period of crater formation, to determine the sequence of emplacement of cratered plains, uncratered plains, and volcanic ridge complexes. If cratering rates on the Moon and Mars are equal, there is the hope that the first approximate interplanetary correlations of geologic events may be possible from crater data. While large impact craters are rare features on Earth, limited radar data for Venus have already revealed the presence of some very large circular structures that may be craters. Thus, some of the Venusian surfaces may be very ancient, and large areas of ancient heavily cratered terrain may exist.

Studies of crater morphology and crater frequency distribution provide clues to the existence of erosive processes and the history of those processes. Typically, there are more small craters than large ones for a normal impact crater distribution and deviations from this distribution may signal certain events. For example, a deficiency of craters in a certain size range could indicate an obliterative process such as wind or water erosion. Conversely, an excess number of craters for a given size range could indicate the presence of nonimpact (e.g., volcanic) craters. There is reason to believe from thermal history models that Venus is differentiated and that volcanic processes have operated. Surface processes related to such agents as wind, water, and downslope movement also might have operated. Both internal (e.g., volcanic) and external (e.g., erosion) processes would leave imprints on the cratering record.

Analyses of small craters (<1 km) on Venus could provide information on the character of its regolith (fragmental surface layer) which would be important to the interpretation of data from future lander missions. If the 100-bar pressure at the base of the Venusian atmosphere has existed for several eons, it will have prohibited formation of primary craters smaller than a few hundred meters (Tauber, personal communication, 1975). In that event, orbiter images must be able to resolve craters smaller than 1 km in diameter because any impact craters detected in this size range would be nonprimary impact craters. This means that, since large areas (100 km^2) of the lunar surface (maria) with ages less than about 3.5 billion years only rarely contain craters larger than 1 km, most similar areas on Venus may also lack craters larger than 1 km. Since primary craters less than 1 km do not form on Venus and since craters smaller than 1 km are responsible for the production of most of the typical lunar mare regolith samples on the scale of 100 km^2, such geologic units 3 to 3.5 billion years old and younger on Venus may contain a regolith generated primarily by secondary craters. Physical properties of

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such a regolith would be quite different from a regolith generated by primary craters; thus the priority to resolve craters smaller than 1 km is very high.

6.1.3.3 Geologic mapping: Unless Venus is completely homogeneous at the surface, its crust will consist of different rock units. That Venus is not homogeneous is evidenced by (1) Venera-8 results indicating compositional differentiation, (2) craters of possible impact origin which would have fragmented the surface rocks and produced crater deposits, and (3) other topographic features that potentially are related to tectonic and/or volcanic processes. In addition, all other inner planets have heterogeneous surfaces and it is reasonable to assume that the same is true of Venus.

The aim of geologic mapping is to understand the enormously complex upper crust of a planet by identifying three-dimensional rock units and by showing their distribution in time and space. Structural elements (e.g., faults) that indicate deformation of the rock units are also shown on geologic maps. From these maps, a succession of geologic events can be determined, and certain landforms (e.g., volcanoes) can provide clues to processes. The units are placed in a relative time scale that shows relative ages (through the sequence of formation) but not the "absolute" age of formation expressed in years. The specific details of how geologic mapping is accomplished is covered by Wilhelms (refs. 95 and 96); the rationale of geologic mapping in planetology is discussed more fully by Greeley and Carr (ref. 97).

The vast majority of extraterrestrial mapping has been accomplished with "normal" images (film, vidicon, etc.) which is not feasible for Venus with its cloud cover. Radar images, however, can also be used for topographic and geologic mapping, as has been recently demonstrated in terrestrial applications. For example, the Amazon basin of Brazil and much of Panama had never been mapped because these areas are covered almost constantly with clouds, and conventional photography is of little value. From radar imaging, however, some rather detailed geological analyses were completed (see, e.g., ref. 98) in which structural features and stratigraphic units were defined. Thus, radar images appears to be amenable to geological mapping on Earth and should be suitable for planetary mapping on Venus.

"Radar mapping" may be enhanced in value over straightforward images, especially in regard to small-scale structure. For example, experience in the lunar case (ref. 99) indicates two applications:

(1) Detection of blocky terrain: The intensity of the depolarized component of the radar return (the component returned to the radar with polarization orthogonal to that expected from a smooth dielectric surface) is highly correlated with blocky ejecta blankets surrounding fresh lunar craters. The radar scatterers are apparently surface and subsurface rocks somewhat larger than the radar wavelength. Detecting orthogonal polarizations represents no difficulty instrumentally; however, data rates must permit both orthogonal-reflected polarizations to be transmitted to the Earth, and this may be a strain on the already taxed telemetry system (see section 6.3.3.3).

(2) Slope analysis: Bistatic radar (ref. 100) involves the analysis of the frequency spread of specularly reflected, directly polarized radiation

transmitted from a spacecraft, reflected from the planetary surface, and received on Earth. The frequency spread is due to the distribution of "facets" on a nominally smooth dielectric sphere with a probability distribution characterized by a mean slope or mean tilt angle. The size scale typified by these mean slopes is on the order of tens to hundreds of wavelengths, that is, meters to tens of meters for S-band wavelengths, a size scale not approached by images. The slopes are not individually observed but are inferred in a statistical sense. In the case of the Moon, there is a significant correlation between radar roughness in mare areas and the mare color (red vs. blue) (ref. 99), thus providing an additional technique for distinguishing geological units. In the lunar case, extremely high signal/noise ratios on the order of tens of decibels were obtained. Thus, despite the much greater distance to Venus, higher radar power and antenna gains relative to those used in the lunar observations will allow meaningful slope estimates to be made. These two techniques, depolarization and bistatic radar, could yield information about the surface of Venus that would be unattainable by even the best proposed images.

6.1.3.4 Active surface processes: Most active surface processes (volcanism, gradation by fluids such as wind or liquids) cause redistributions of materials which could show as changes in the dielectric constant because of changes in composition, grain size, and density. The possibility of aeolian transport on Venus should not be overlooked. Near-surface winds on Venus may be limited to about 10 cm/sec based on the work of Ainsworth and Herman (ref. 21); however, results from Veneras 9 and 10 show that winds of several m/sec occur. A calculation of the minimum threshold speed required to set particles in motion under Venusian conditions gives approximately 2 cm/sec at the surface. Such velocities should be expected on Venus, particularly near topographic landforms where vortical winds might occur, thereby suggesting aeolian transport. The windblown patterns observed on Mars during Mariner 9 probably could have been detected by radar because of the probable change in soil properties. Thus, if the resolution is sufficient, radar instruments on a Venus orbiter could be used to detect surface change, which, when combined with images, could be interpreted as specific surface processes provided that repetitive coverage is available. Additional information obtained inferentially by methods described in the previous section could also be used to investigate time variations on a smaller scale (e.g., coverage of regions of rubble by dust or vice versa).

6.1.3.5 Other surface data: In addition to observations of surface morphology, the possibility of obtaining data on other surface properties from orbit was investigated.

Measurements of the microwave flux from the planetary surface can be used to deduce near-surface temperature. This deduction makes use of the values of the dielectric constant independently determined by a radar mapper for the same areas to obtain an emissivity ($E = 1 - \eta$) from the Fresnel reflectivity (η) at normal incidence. The radar reflectivity, R, is normally written $R = g\eta$, where g is the backscatter gain over an equivalent smooth surface and is a function of surface roughness on the scale of several to many wavelengths. Consequently, this is a further justification for the roughness

studies discussed in the previous section. Accurate knowledge of the emissivity requires accurate knowledge of the surface roughness to radar. Because diurnal variations in surface temperature are not expected on Venus, any variations seen would probably be due to geothermal activity or elevation differences.

It is possible, however, to estimate the minimal performance of an orbiting microwave radiometer for mapping thermal variations. Venus is relatively "smooth" to radar at centimeter wavelengths over much of the surface, and the contribution to the Earth-based radar reflectivity from directivity or roughness effects appears to be on the order of 10 percent (see, e.g., ref. 101). We assume that the uncertainty in reflectivity is limited by the uncertainty in the directivity and set this value conservatively at 5 percent. Allowing for a 1-percent flux measurement error, it would be possible to obtain physical regolith temperatures with, at worst, a 6-percent uncertainty (equivalent to about 40° K). If roughness (directivity) becomes well understood, we are left with a 1-percent measurement error in reflectivity and thus 2 percent net uncertainty in temperature (about 15° K). The spatial resolution of the radiometer (a function of the size of the radar antenna and wavelength of operation) typically would be on the order of 10 km at periapsis, and the region sensed is typically several meters below the surface. By terrestrial analogy, thermally active areas would be detected with this spatial and thermal resolution, even in the "worst case."

Variations of temperature with elevation would be sensed, assuming a lapse rate of 8-9° km^{-1}, with an elevation resolution of ~2 km, assuming the surface directivity can be extracted and the "best case" accurate emissivity values may be obtained from radar reflectivities.

It does not appear that any significant additions to hardware, power, or data-handling capability would be required by the above experiment if operated in conjunction with the radar.

We also investigated the possibility of mapping surface composition using values of dielectric constant obtained from orbit and surface porosity measured from landers. It appears to be impossible quantitatively to determine a value of porosity from a simple lander (i.e., penetrometer), and direct chemical analysis appears to be the only definitive technique for determining composition. One of the most curious facts about Venus, known for several years from Earth-based radar and radio observations, is that the dielectric constant of the surface material is significantly higher than that of any other planet. The dielectric constant (ε) for Venus is $\varepsilon = 3.7 \pm 0.3$, compared with 2.2 ± 0.2 for the Moon, 2.5 ± 0.2 for Mars, and 2.4 ± 0.2 for Mercury. It is not known whether this difference reflects a difference in regolith porosity or composition. Temperature may affect the dielectric constant or absorption length, related to conductivity (ref. 102), of the surface material. No such effect has been observed for the regolith of Mercury, however, which attains equally high surface temperatures, but the high temperature in the Venus subsurface prevails to greater depths than for Mercury. In addition, laboratory measurements of material properties at elevated temperatures indicate that, although there is some temperature dependence, the degree and even the sense of the variation with temperature is material-dependent.

6.1.3.6 Data requirements - surface mapping: Questions regarding the morphology, physiography, geologic mapping, crater frequencies, presence of tectonic and volcanic features, and derivation of the geologic history suggest that contiguous images for at least 90 percent of the planet at a resolution of 1 km or better and selected nested imagery to scales better than 100 m are highly desirable goals. These goals can be met with an orbiting radar mapper.

Resolution is a difficult parameter to assess, particularly in terms of radar pictures. With conventional photographs obtained with film systems, resolution is stated in terms of separable white-on-black line pairs per millimeter on the image. For spacecraft vidicon systems (e.g., Mariner 9 - Mars; Mariner 10 - Mercury), the scale width of a single television line at a particular altitude is often used as the index to system resolution. In both cases, other factors such as Sun elevation, shape, and sharpness of outline must also be considered as recognition factors. Many of these parameters are not applicable in discussions of radar images, and it is difficult to compare resolutions of one system to another. Nevertheless, it is useful to discuss in general terms the resolution requirements for different objectives. Figure 29 shows the resolution range for optimum characterization of selected lunar features. It is apparent that, to characterize the general morphology, to determine crater frequency distributions, and to accomplish regional geological mapping, contiguous coverage with a resolution between 0.8 and 1 km is required. Resolutions between 10 and 100 m are required before most landforms can be identified and before definitive statements can be made about specific processes. For example, in the case of Venus, the definition of impact craters smaller than 100 m would signal secondary crater formation (as discussed above).

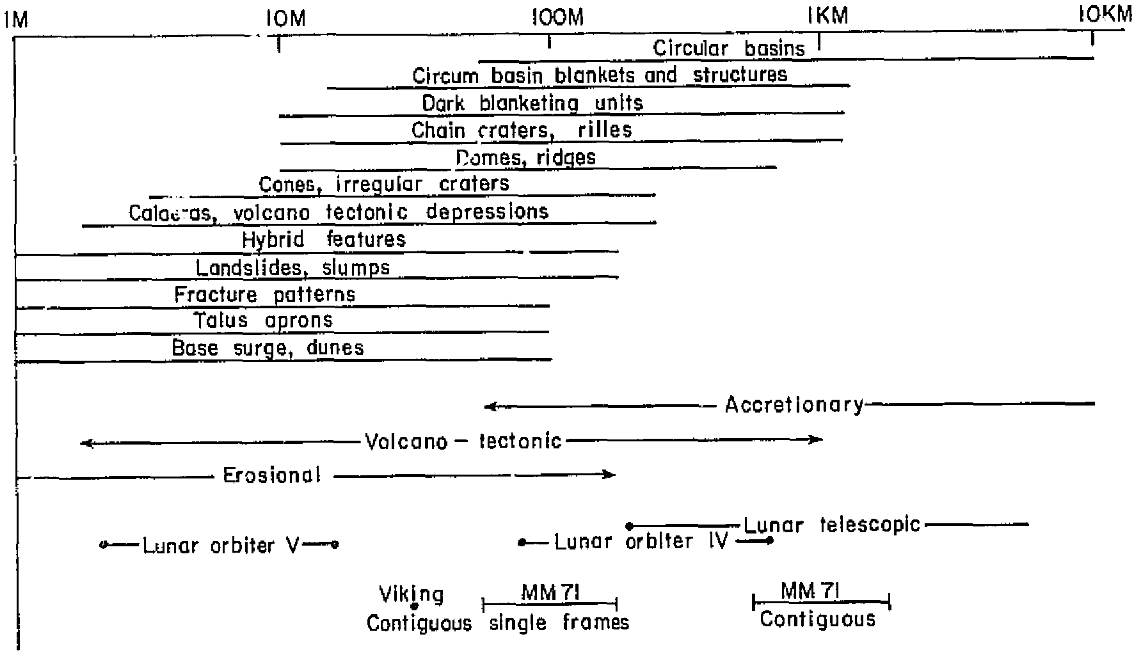


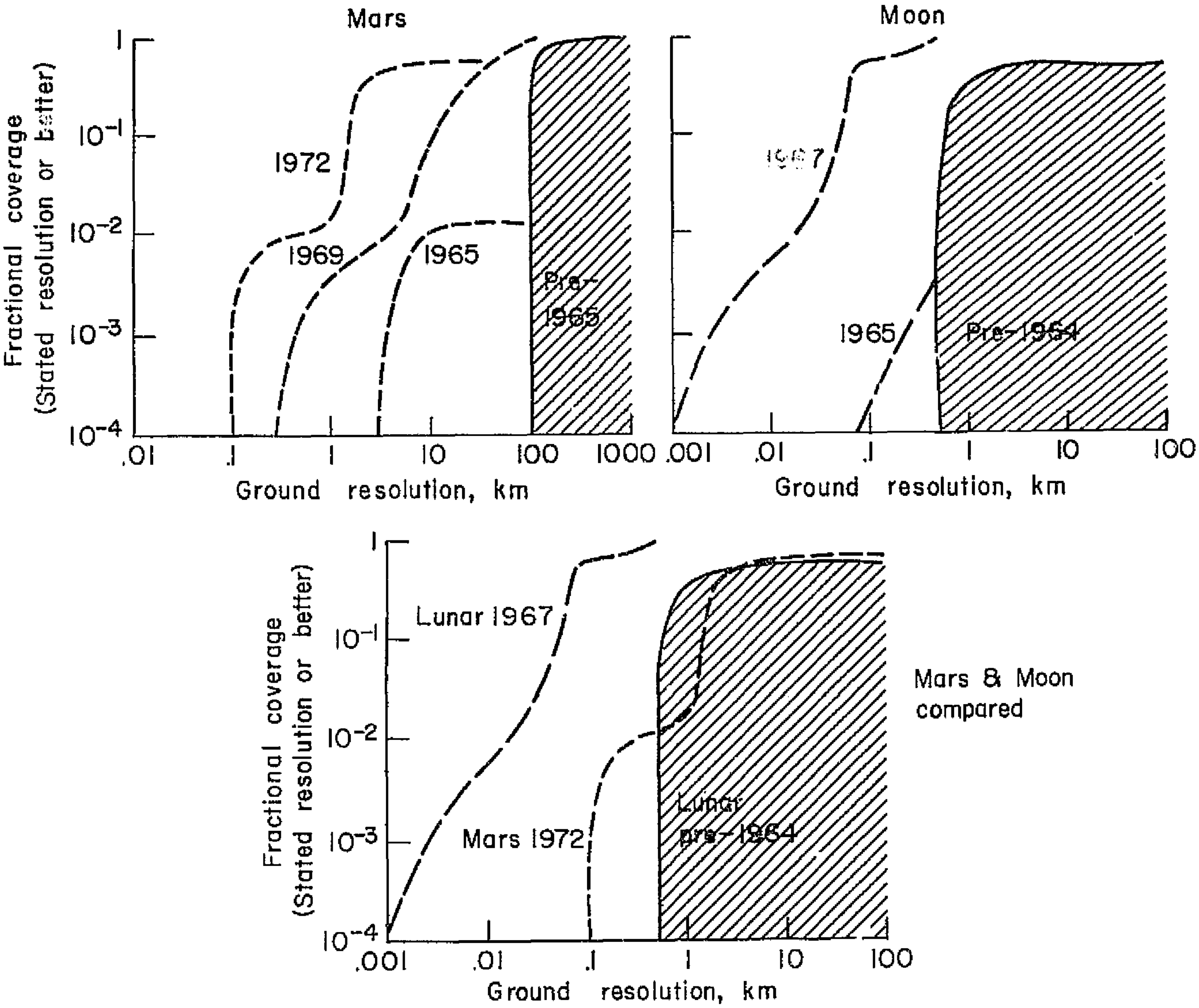
Figure 29.- Resolution range for optimum characterization of selected lunar features compared with the resolution of imaging from different sources. (After Masursky et al. (ref. 103).)

Murray (ref. 104) provides an excellent discussion of the resolution and coverage needed for different levels of data interpretation. The extraterrestrial body for which we have the most information is the Moon. The Moon has served as a "training ground" for planetology and serves as a useful example for the type of data required for meaningful interpretations. Figure 30(b) is a plot of coverage versus resolution for the Moon obtained from Earth-based observations and lunar missions (ref. 104). As can be seen, each increase in coverage and resolution permitted a clearer understanding of the general properties and history of the Moon. Figure 30(a) is a similar treatment for Mars. Most planetologists were misled by the data from Mars flybys Mariners 4, 6, and 7, which sampled a total of about 10 percent of the planet at 1-km resolution. This sampling just happened to hit the cratered plains, leading most investigators to view Mars as another Moon in terms of its surface morphology and history. It was not until the representative global coverage from orbiting Mariner 9 that Mars became known as a planet involving many complex processes strikingly different from both the Moon and Earth. Finally, figure 30(c) compares the Moon and Mars, where it is clear that, even on Mars after Mariner 9, we have barely reached the pre-space-age coverage that was available for the Moon. In the case of Mars, this was sufficient to positively identify volcanic features; in the case of the Moon, it was not. Note, however, that nested high-resolution (~100 m) frames were available for Mars. In addition, on Mars, the Mariner-9 coverage and resolution were sufficient to show active surface processes (dust-storm activity).

Although it is difficult to speculate on what the exact coverage and resolution should be for Venus, it is clear that the minimum should be comparable to that of Mariner 9 for Mars.

6.1.4 Interior - Future orbiter missions will provide gravitational data as a matter of course. If Venus is as gravitationally smooth as the Earth, the maximum geoid heights (the displacements of an equipotential from a reference surface) would be measured in tens of meters (ref. 105). Such resolution should be obtainable by Doppler tracking of a spacecraft with a periapsis altitude of several hundred kilometers or less. Horizontal resolution is approximately equal to the periapsis altitude; since Pioneer Venus will have a periapsis close to the minimum obtainable (as limited by the Venusian atmosphere), substantial improvement in horizontal resolution is unlikely. However, large areas of the planet will not be mapped by Pioneer Venus; therefore, the orbit of a future mission should be chosen to complement the coverage of that mission. This would require periapsis in the southern hemisphere. Orbits with low eccentricity are generally desirable for gravitational mapping.

The inclusion of a dual-frequency radar for gravitational mapping by the method proposed by Shapiro et al. (ref. 106) should be considered. In this experiment, the gravitational shape of Venus is determined by comparison of radar reflection intensities at the two frequencies. Because the absorption of radio waves by the Venusian atmosphere depends strongly on frequency, constant pressure contours can, in principle, be determined from the relative intensities of the reflected signals at different frequencies. The absolute levels of the contours with respect to the mean planetary radius are found from measurements of the echo delay. To do all this, it is necessary to



(a) Resolution vs. coverage: Mars imaging coverage vs. resolution plots for pre-1965 Earth-based (shown stippled), 1965 extension by Mariner 4, 1969 increase by Mariners 6 and 7, and 1972 increased by Mariner 9.

(b) Lunar imaging coverage vs. resolution plots for pre-1964 Earth-based (indicated by stippling), 1965 extension by Ranger and 1967 increase due to Lunar Orbiter coverage.

(c) Coverage vs. resolution plots showing present status of the Moon and Mars compared to pre-space-age coverage of the Moon (shown stippled).

Figure 30.- Resolution vs. coverage (after Murray (ref. 104)).

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specify the atmospheric absorption coefficient as a function of the variables of state and to model the structure of the lower atmosphere. This should be possible with information gained from the Pioneer Venus mission. Although low-altitude weather systems are not expected on Venus, atmospheric tides or other forms of gravity waves that penetrate the lower atmosphere might introduce difficulties. Note that vertical topographic resolution better than tens of meters is required to resolve the variations in the Venusian gravity field by this method, if the field is as smooth as the Earth's.

Gravitational and topographic data can be analyzed together to provide important information on the degree of compensation of surface features, and, by inference, the mechanical and thermal properties of the subcrustal material, as has been done for Mars (ref. 107). For this reason, radar altimetry should be included on a post-Pioneer Venus orbiter mission. Vertical resolution comparable to the gravitational (geoid height) resolution is desirable and should be obtainable.

6.2 Instruments

Instruments that are required to address the questions outlined above are discussed here. Primary emphasis is given to discussion of spacecraft-borne radar imaging systems similar to the airborne side-looking imaging radars used on Earth, which are capable of producing about the same image quality.

6.2.1 Venus orbiting imaging radar (VOIR) - The Venus orbiting imaging radar (VOIR) currently under study by JPL is a synthetic-aperture radar (SAR) mounted on a three-axis-stabilized orbiting spacecraft. The spacecraft is placed in either a circular or eccentric polar orbit. The slow rotation of Venus beneath the spacecraft allows nearly the entire surface to come within view of the radar within about 122 days of the mission for near-circular orbits. Figure 31 shows a representative spacecraft and radar configuration. In this configuration, a single antenna is alternately used for radar and telemetry; in other mechanizations, separate dedicated antennas are used.

The synthetic-aperture radar produces high-resolution maps of surface or near-surface microwave reflectivity by directing a beam down and to one side of the spacecraft flight path (fig. 32). The radar receives a time distribution in reflected energy as each radar pulse travels through the beam footprint on the surface. This permits the footprint to be resolved into zones equidistant from the spacecraft radar (as shown in the figure). It is possible, in addition, to subdivide the beam into azimuth bands by means of the Doppler frequency shift. The return from points exactly normal to the spacecraft motion is not shifted in frequency since there is no velocity component in that direction. Scatterers ahead of the spacecraft will produce a positive shift, while those to the rear, a negative shift. By proper processing then, the footprint may be subdivided into range and azimuth "bins."

A succession of radar pulses is transmitted, and the backscattered signals are recorded in a sequence of positions along the flight path. These records are similar to the signals received by the elements of a linear antenna array and, by proper phasing, a "synthetic array" may be constructed.

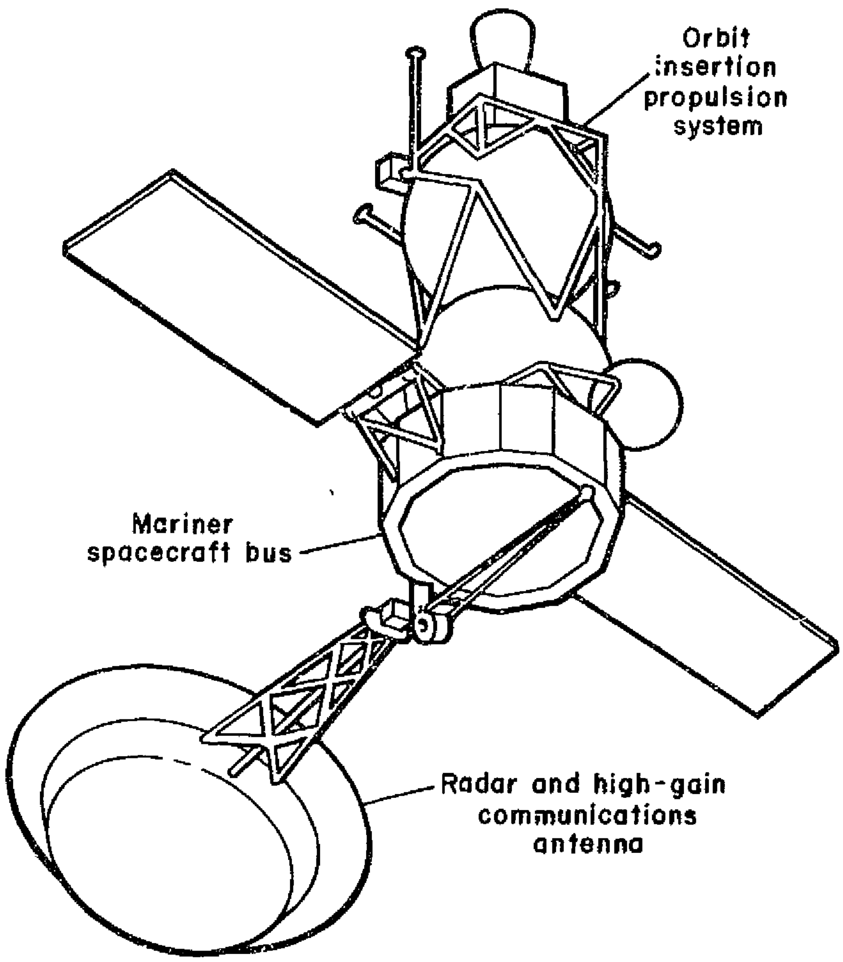

Figure 31.- Typical VOIR spacecraft.

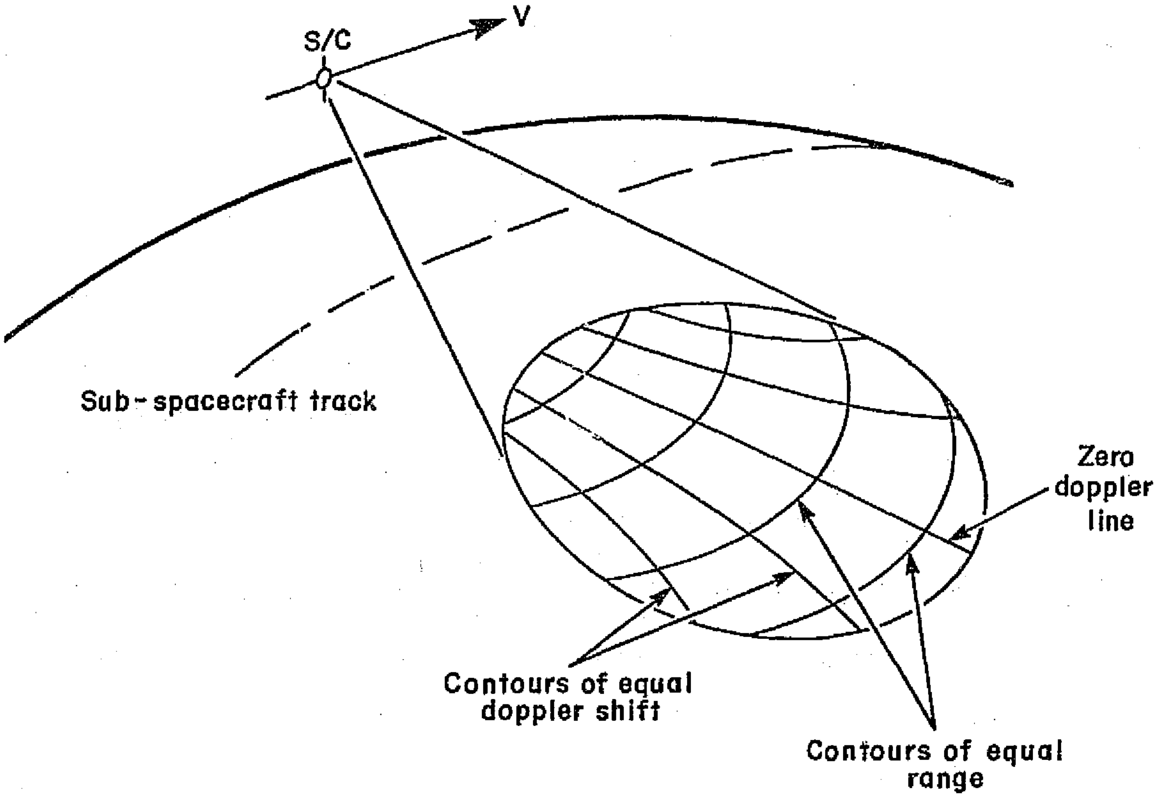

Figure 32.- Radar imaging principles.

The fact that these returns are received over a period of time, rather than simultaneously as in a real array, is of no consequence, provided phase coherence is maintained over the integration period and provided the target is stationary.

In all orbits, including circular orbits, one axis of the spacecraft, or the antenna, must be continuously controlled in angle to maintain the mapping geometry. With an eccentric orbit, mapping is accomplished only near periapsis in order to minimize radar power. At the beginning of the mapping cycle, the radar antenna must be oriented along the direction of zero Doppler. This permits correct registration of sequential mapping swaths. If the antenna is pointed in any other direction or if the orientation changes during the mapping cycle, compensation for the map offset must be provided in processing. Other elements of the orbit selection and the resulting coverage limitations are discussed in section 6.3.

The Venusian atmosphere increasingly attenuates wavelengths shorter than 1 m (ref. 108), although surface radar reflections have been obtained at wavelengths as low as 3.8 cm. A choice of radar frequency must consider the degree of surface penetration by the radar waves (ref. 109) as well as the impact on spacecraft subsystems. The operating wavelength will probably lie in the range of 10 to 25 cm (refs. 88, 109, and 110); the actual operating frequency will depend on the results of detailed tradeoff studies.

Within limits, the range and azimuth channels may be considered to be independent. The range channel operates like a conventional pulse radar, and the range resolution thus depends on the radar pulse length. By pulse compression, an effective pulse length of 0.1 to 0.5 μsec is possible, which would permit a range resolution of 15 to 50 m. The estimated atmospheric turbulence limits the ultimate surface resolution to about 10 m (ref. 111).

The azimuth resolution is a function of the amount of data processed to produce the synthetic aperture. The best surface resolution that can be obtained in the azimuth (along-track) direction is half the length of the real antenna (which cannot, however, be reduced arbitrarily), and the resolution degrades proportionately as fewer data are processed (ref. 112). Azimuth resolution comparable to range resolution is usually acceptable, however, and results in acceptable data transmission and processing requirements.

One major difficulty with the use of synthetic-aperture radar (SAR) lies in the relatively large radar antenna dimension required in the direction of spacecraft travel. This results from a requirement to limit the beamwidth to prevent angular ambiguities. Recent studies, however, have found designs that permit reduced antenna sizes (Friedman, personal communication, 1975).

A high telemetry load is required because of the difficulty in implementing the sophisticated processing required for synthetic aperture mapping on board the spacecraft. (The feasibility and technology requirements for onboard processing of images is currently under investigation.) The surface resolution is directly related to the telemetry rate required to support it. For eccentric orbits, rates as low as 70 kilobits/sec are adequate; for circular orbits rates between 250 and 500 kilobits/sec are usually used. The

higher rates for circular orbits result from mapping the planet in half the time and from increased occultation periods compared to an eccentric orbit.

6.2.2 Synthetic aperture radar from spinning spacecraft - Synthetic-aperture radar (SAR) design and processing are most easily accomplished with a fixed geometry. Mapping a spherical planet from an eccentric orbit complicates the problem in that the changing geometry results in a changing direction of the zero-Doppler line, changing swath width, and changing pulse repetition frequency limits due to ambiguities. Use of a spin-stabilized spacecraft as a platform for a SAR provides two additional complications. First, since the spacecraft is spinning, the time available to construct a synthetic aperture is limited. Second, it is difficult to control the inertial orientation repetitively.

The three primary spin-axis orientations that can be considered for mapping from a spin-stabilized spacecraft are shown in figure 33. With orientations (a) or (b) and a high spacecraft spin rate, there is only a limited time for the radar signal to illuminate the desired ground swath before the beam rotates, while with a low spin rate the spacecraft will have moved in its orbit. In either case, it may be possible to synthesize only a short aperture, with a resulting loss of resolution. Orientation (c) avoids these problems since the spin axis is directed along the beam centerline. However, unless the spacecraft is torqued throughout the mapping cycle, or unless the radar antenna is articulated, the planetary coverage is restricted. Any of these approaches would be difficult to implement with a spinning spacecraft.

A study sponsored by Ames Research Center is currently being conducted by the Environmental Research Institute of Michigan to evaluate the coverage, resolution, and general feasibility of SAR from a spinning spacecraft.

6.2.3 Synthetic array, real array hybrid (SARAH) from a spinning spacecraft - A conceptual design for a dual mode (high and low resolutions) radar that could be incorporated into a spin-stabilized spacecraft is described below. This concept was developed by the Radar Avionics organization of the Hughes Aircraft Company.

A typical configuration for the proposed spacecraft is shown in figure 34. The concept consists of a Pioneer class spacecraft with one large, folding, planar antenna array spinning with the spacecraft and a despun telemetry antenna. The despun antenna is also used as the receiving array for operating the radar system in the high-resolution mode. The planar array is used for transmit/receive in the low-resolution mode and transmit in the high-resolution mode. This planar antenna is comprised of two separate antennas; an antenna 3-12 cm high that generates a wide beam for the low-resolution mode and an antenna 15-60 cm high that generates a narrow beam for the high-resolution mode. The actual size of the planar array is dependent on wavelength and radar-processing techniques. For x band, the array is about 7 m long, whereas for s band it can be as long as from 17 to 30 m. Additional system design and tradeoff studies are required to minimize antenna size.

The high-resolution mode, which uses a section of the planar antenna for the transmit function and the despun antenna for receive, operates similar to

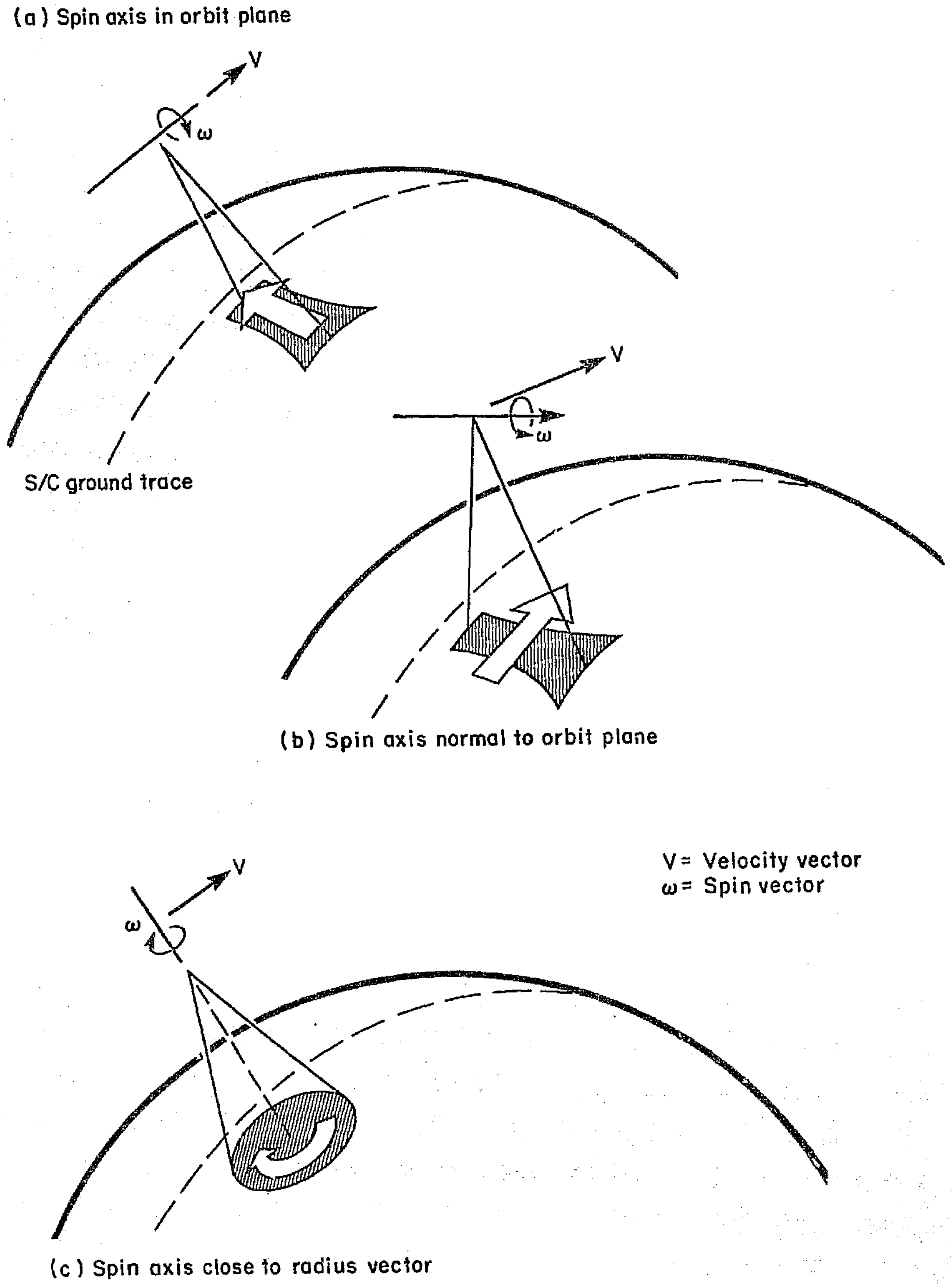

Figure 33.- Spin orientations.

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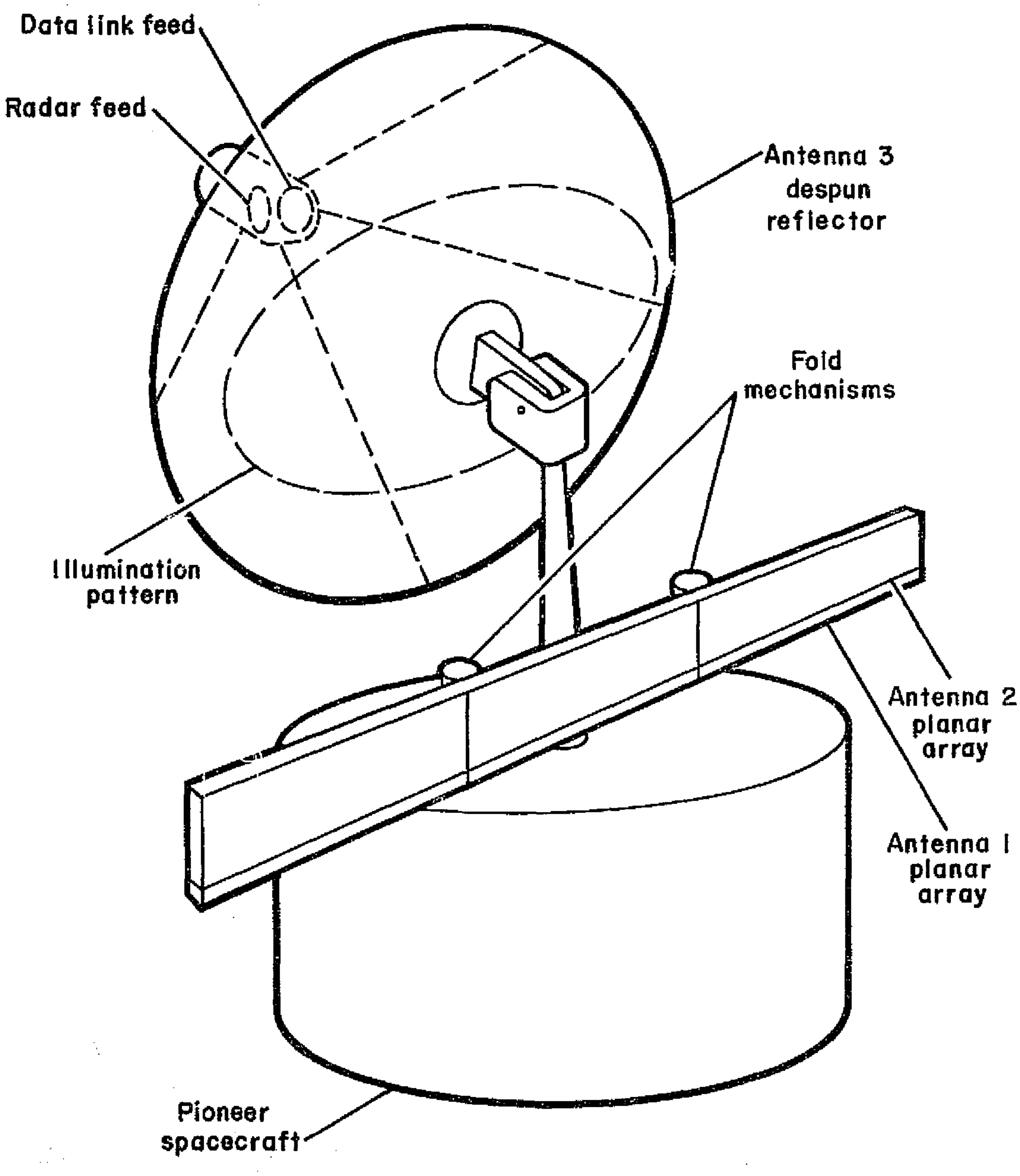

Figure 34.- SARAH version of Pioneer class orbiter.

the SAR systems previously described. For the low-resolution mode, the large, highly directional spinning antenna is used to obtain narrow angular mapping of the range (crosstrack) coordinate. (The spacecraft spin axis is oriented along the velocity vector at periapsis.) The azimuth (along track) coordinate is obtained by SAR processing. The use of continuous wave (CW) rather than pulse radar removes the restriction on the Doppler sampling rate, so that a small antenna dimension may be used in the direction of spacecraft travel. The range resolution can be increased by using one of several pulse coding techniques, this would tend to reduce antenna length at the expense of increased system complexity. This approach, along with other system tradeoffs, requires further examination in system feasibility studies.

As an example, assume that the spacecraft is placed in an elliptical orbit with a periapsis altitude of 200 km (at the equator) and an orbit eccentricity of 0.3. At 30° north and south latitude, the orbit altitude is approximately 400 km. For a system designed to operate in the altitude regime between 200 and 400 km, the radar will map 50 percent of the entire planet in one Venus sidereal day (~243 Earth days). For higher latitude coverage, periapsis must be moved to higher latitudes. With periapsis at +60° latitude, the mapper will cover the entire region from +30° to the pole in a second sidereal day. Finally, if possible, the orbit must be moved to place periapsis to -60° latitude to cover the remaining polar region in a third sidereal day.

In both the high-resolution and low-resolution modes, the radar will radiate approximately 65 W of average power. This will require a transmitter input power of approximately 180 W and a total radar power requirement of approximately 200 W. A data rate of approximately 50-70 kilobits/sec is needed to transmit the above data.

6.2.4 Instruments from the Pioneer Venus orbiter mission - The principal objectives of the Pioneer Venus orbiter mission concern data-gathering for the ionosphere, solar-wind interaction, atmosphere, and cloud physics. It is generally felt that follow-on orbiter missions should essentially repeat these experiments to gather additional information for the problem areas remaining after the Pioneer Venus mission (both anticipated and unexpected problems). Follow-on orbiter missions should occur during solar minimum to complement the Pioneer Venus mission data that will be acquired during solar maximum. For the most part, the same instruments can be used. However, from the discussion in section 6.1, it is clear that more instrument capabilities would be valuable in certain instances and a need for further development exists in those cases. Detailed summaries of the experiment descriptions for Pioneer Venus are given by Colin and Hall (ref. 113).

6.3 Engineering Considerations

6.3.1 Radar mapping missions - The primary objective of the radar mapping missions is to image at least 90 percent of the surface of Venus at 100-1000-m surface resolution and to image a targetable 5-20 percent of the surface at 10-100-m resolution. Continuous altimetry and up to 30 percent stereo overlap

at the equator are desirable. To meet these objectives, a radar mapping mission would use a side-looking radar system similar to those described in section 6.2.

Launch opportunities are available approximately every 19 months. The duration of the interplanetary phase of such a mission is approximately 4 months, while the duration of the orbital phase depends on the orbit and system selected. The minimum time in orbit to meet the coverage objective is about 4 months for a circular orbit and about 8 months for an elliptical orbit.

6.3.2 Orbit considerations - The objectives of a Venus radar mapping mission require that the spacecraft be in a near-polar orbit. This spacecraft serves as a platform for a radar that is directed down to the side of the spacecraft flight path. The antenna or the spacecraft must be rotated continuously throughout the orbit to maintain near-nadir pointing. The planet slowly rotates beneath the inertially fixed spacecraft orbit; this provides a means of sequentially scanning overlapping radar swaths of the planet surface. Not every orbit need be used for mapping purposes; nonmapping orbits can be used for other science and for data telemetry.

The required width of the radar swath is a function of the required swath overlap, orbit altitude, and the time between mapping orbits. An overlap of 10 to 30 percent should be adequate to permit good topographic registration. A wider swath or greater overlap increases the radar power necessary to provide an adequate signal return.

Some stereoscopic information is obtained with overlapping swaths due to the change in angle to the mapped area. Wide-angle stereoscopic coverage would require looking to either side of the spacecraft, either simultaneously or sequentially. The former approach would have an unacceptable impact on spacecraft mass since the radar system would be essentially duplicated. The latter approach could be accomplished by mapping alternate sides on alternate orbits or by using a spinning spacecraft. A third approach would be to map the planet twice. Currently, only the limited stereo coverage obtained by overlap is considered in the baseline designs.

The spacecraft orbit is another major factor in system performance. An eccentricity between 0 (circular) and 0.6 is acceptable for this mission. The upper limit is necessary to ensure orbit stability under solar perturbations (ref. 109). While a low-altitude orbit is desirable to decrease radar power, a minimum altitude constraint must be imposed to preclude altitude decay due to atmospheric drag. The current choices for the periapsis altitude range between 400 and 500 km.

A circular orbit provides complete planetary coverage with a mission duration of 1/2 a Venusian rotation period (122 days). The radar design and operation, as well as image reconstruction, is simplified since the mapping geometry does not change during the mission. The difficulty with a circular orbit, for the 600 to 900-kg spacecraft (which is estimated would be required for this application using a three-axis-stabilized spacecraft), lies in the large retropropulsion system needed for orbital insertion. Table XXII shows the net weight in orbit for two orbit eccentricities, for various Titan and Shuttle class launch vehicles, and for a range of mission opportunities in the

TABLE XXII.- VENUS ORBITER MISSION PAYLOAD POTENTIAL

Launch vehicle	Orbit eccentricity	Net mass in Venus orbit, kg									
		Year of launch opportunity									
		1976 (86)		1979 (87)		1981		1983		1984	
		Onboard propulsion, Earth storable (ES), or space storable (SS)									
		ES	SS	ES	SS	ES	SS	ES	SS	ES	SS
Titan IIIE/Centaur	0	738	1071	536	810	735	1080	800	1161	836	1197
	.5	1666	1955	1347	1484	1674	1980	1802	2118	1863	2172
Shuttle/Transtage	0	598	874	344	516	627	927	711	1035	742	1067
	.5	1366	1606	820	971	1441	1706	1610	1893	1665	1943
Shuttle/Centaur	0	1342	1925	991	1432	1345	1953	1479	2123	1542	2187
	.5	2963	3470	2213	2598	2996	3535	3264	3825	3371	3923
Atlas D/Centaur	.8[a]	295	322	---	---	330	362	380	414	394	426
	∞[b]	800	800	800	760	600	600	650	650	650	650

NOTE: For the first day of the opportunity and periapsis of 400 km except for Atlas D/Centaur where:

[a]denotes 24-hr orbit

[b]a flyby.

A flyby uses a different launch period.

1980's (ref. 114). The table shows that, for the Titan IIIE/Centaur, about 735 kg may be placed in a circular orbit in 1981 using a Viking-type, Earth-storable propulsion system. This provides very little weight margin based on current estimates of spacecraft mass. The insertion stage size and thus launch mass requirements decreases substantially with increases in orbit eccentricity; this factor can be used in actual mission design as a variable to match launch vehicle delivery and spacecraft mass requirements. Increased weights in circular orbit could also be achieved by means of a new high-energy, space-storable stage or by the use of a Shuttle/Centaur launch system. The mass capabilities of these options are shown in the table and range between 800 and 3900 kg, depending on the mission opportunity.

Some of the above options require technology developments, which must be justified on the basis of the additional planetary coverage offered by a circular orbit and by the decreased radar system complexity, as compared to an eccentric orbit. Further tradeoff studies are required.

6.3.3 Radar mapping from a three-axis-stabilized spacecraft - A Venus Orbital Imaging Radar (VOIR) mission represents a means of meeting the needs for the exploration of Venus for those areas that require imaging of the surface at the resolution limits specified above. This mission has been analyzed in several studies (refs. 109, 111, 115, and others). A conceptual design of a typical VOIR spacecraft is shown in figure 31.

6.3.3.1 System design: The spacecraft subsystems required to support the radar and data-handling functions can be relatively straightforward derivatives of other three-axis-stabilized spacecraft systems such as the Viking 1975 orbiter. The estimated mass for a typical configuration is shown in table XXIII.

TABLE XXIII.- THREE-AXIS SPACECRAFT MASS SUMMARY

		Mass (kg)
Structure, mechanical devices, and thermal control		275
Radar		45
Communications/command/mod demod		43
Data handling		36
Attitude/articulation control		83
Power/pyro		144
Spacecraft adaptor		34
Spacecraft mass (usable mass in orbit)		660
Orbit eccentricity	e = 0.5	Circular
Propulsion system inerts (including contingency)	258	365
Propellant (Earth storable)	1708	2405
Launch mass	2636	3440

In 1983, the required launch C_3 for a 20-day window is ~10 km^2/sec^2, which gives an injected weight from the shuttle/IUS and Titan/Centaur that ranges from 3000 to 6000 kg, respectively (see appendix B). The required

launch mass for typical elliptic and circular orbit configurations (table XXIII) are about 2600 and 3500 kg, respectively. Thus the Shuttle/IUS (two stages) can deliver this spacecraft to an eccentric orbit but would have difficulty with a circular orbit; a Titan/Centaur or a Shuttle/IUS (three stages) is required for circular orbits.

6.3.3.2 Radar and antenna system: The radar uses a side-looking synthetic-aperture system mounted on an inertially stabilized platform. The radar system was described in some detail in section 6.2.1. (Radar characteristics, including the operating frequencies, will be selected on the basis of detailed system tradeoff studies.) The current system designs assume a single frequency and a single polarization, which can be modified later if required. The development of the imaging radar for the SEASAT program should improve the readiness state for radar technology for the Venus mission (ref. 114). A simple radar altimeter is required to provide basic data for image rectification, stereo images, and limited sounding. The altimeter will use a separate small antenna and, to utilize existing systems, will probably operate at L-band frequencies.

6.3.3.3 Data handling and communications: The radar data processing, data storage, and return data link are the most sophisticated and demanding parts of the radar mapper system design. A typical strategy for onboard processing involves receiving raw data from the radar at 6 to 12 Mbps, presuming or averaging to approximately 500 to 1000 kbps, storing the data with a capacity of approximately 1100 Mbits, and transmitting to Earth at rates up to 500 kbps.

Because of the variation in the Venus-Earth range during the mission and the resulting variation in possible data-link rates, several alternative strategies can be used. During the long-range portion of the mission, presumed azimuth and unprocessed range data can be transmitted to yield resolutions of 100 × 100 m. At shorter range, when available data rates increase, the additional capacity can be used for finer azimuth resolution or for mixed-integration ground processing. The communications system can use the high-gain radar antenna with a separate x-band feed. (The antenna can be pointed toward the Earth during the nonmapping phase of the mission.)

6.3.4 Radar mapping from a spin-stabilized spacecraft - The engineering requirements of a spin-stabilized radar mapping system have not been examined in depth; however, preliminary analysis indicates that this approach is compatible with a Pioneer-class vehicle. This mission must be dedicated to the mapping function, and other experiments turned on only after the radar mission is completed. The communications system does not operate during the short mapping phase; therefore a data storage system is necessary. One 85-W x-band transmitter, along with a 0.75-m mechanically despun antenna, is required to support the data rate of approximately 70 kbps for this mission.

Operational control of the spacecraft is maintained by Earth commands. The radar and antenna configuration will vary, depending on the spin orientation used and on whether an approach similar to the SARAH system (described in section 6.2.3) is used. In the latter case, a new planar antenna design may be required. A weight summary for a spin-stabilized SAR system is given in

table XXIV (includes sufficient propellant to achieve an orbit with an eccentricity of 0.3). The mass of this spacecraft is estimated to be only about half that of a three-axis-stabilized spacecraft. In 1983, the required launch C_3 is ~10 km^2/sec^2; thus this spacecraft can be launched with the Atlas/Centaur/TE-364-4 instead of a larger more costly vehicle.

TABLE XXIV.- ESTIMATED SPIN SPACECRAFT MASS SUMMARY

		Weight (kg)
Structure, harness, thermal		120
Communications		21
Data handling, recorder		50
Controls		30
Power		46
Command		10
ACS		9
Propulsion		21
		307
Contingency		22
ACS gas		21
Radar and antenna		50
	Spacecraft	400
Propellant (e = 0.3)		620
		1020
	Attachment	35
	Launch weight, kg	1055

6.3.5 Technology requirements - Most of the subsystems used for the radar mapping mission are based on current technology with the possible exception of the large folding planar antenna required for the spin-stabilized SARAH system. Development testing will be required to verify adequate performance margins under the conditions of the Venus mapping mission.

Several potential system performance enhancement features, identified by Scofield and Cross (ref. 110), are listed below. Some of these will require additional development:

- Control moment gyros and reaction wheels to minimize gas usage by the ACS system
- Advanced low-power, long-life data storage systems
- High-power x-band telemetry amplifiers
- High-data-rate, high-code-rate convolutional decoders
- Furlable, articulated, large-diameter antennas
- Space-storable propulsion systems

- Ambiguity-elimination and power-reduction methods to be used for radar mapping in elliptical orbits

- Methods for determining image content (especially topographic data) as a function of frequency, polarization, resolution, side-look angle, and stereo enhancement

- Onboard radar image processing systems

6.3.6 Nonradar science Venus orbiter missions - In addition to the radar imaging mission, other orbiter missions have been identified for the post-Pioneer Venus time frame. These are of two types: independent orbiters and orbiters used as buses for transport and operational support of entry probes, balloons, and landers. These latter orbiters would carry their own science instruments in addition to those used in their support function.

Pioneer-class orbiters are generally satisfactory for either of these purposes. They could be essentially identical to the Pioneer-Venus orbiters except for modifications in the instrument complement and capability. If an orbiter mission is considered as an independent mission, it would be desirable for launch to occur near solar minimum. For such an orbiter, mission operations would be similar to those for Pioneer Venus. The orbiter would be injected into a high inclination orbit with a periapsis altitude between 150 and 400 km and would make repetitive measurements for approximately one Venus spin period (243 days).

If the orbiter supports other payloads (such as probes, balloons, or landers), the requirements of supporting those payloads are primary and will generally determine orbit characteristics, mission timing, and available weight for scientific instruments payload on the orbiter. In some of these cases, relay communication from the entering payload is a required supporting function of the orbiter.

6.4 Recommendations

Despite numerous planetary probes in the past and the anticipated results from Pioneer Venus, Venus remains as the last of the geologically unexplored inner planets. The normal sequence in planetary exploration is (1) initial reconnaissance with flyby missions, (2) global exploration with orbiting spacecraft, and (3) detailed in-situ analysis for selected regions by landed spacecraft. For geological exploration, imaging plays a critical role in all three categories of missions and is generally the dominant experiment on orbiters. The cloud cover on Venus dictates the use of radar imaging systems that have not been flown on previous missions.

To a degree, Earth-based radar imagery will fulfill the initial reconnaissance phase (fig. 35). However, neither Earth-based radar results nor the radar data from Pioneer Venus will be an adequate substitute for global images at the resolutions required. Therefore, the highest priority for a post-Pioneer Venus missions is placed on an orbiting spacecraft containing a radar

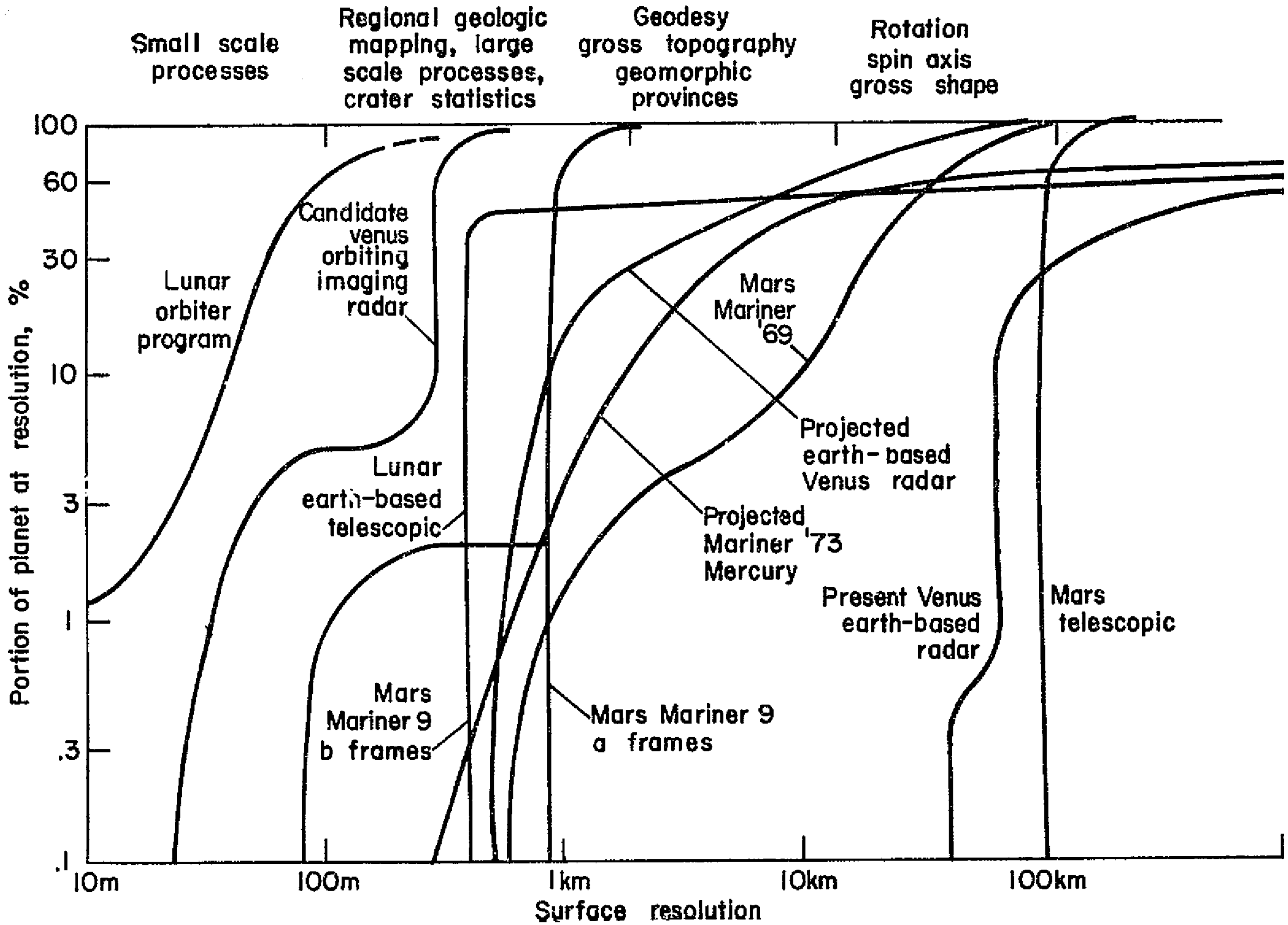

Figure 35.- Laying out a strategy for Venus exploration is helped by comparing it to Mars and lunar mapping. Better resolution extends our knowledge to fields listed farther to the left at the top of the figure. Resolution here means the linear dimension of a side of an areal cell sufficient for identification (from Friedman and Lewis, ref. 114).

system capable of producing high-resolution images. Desirable goals for such a mission would include resolution on the order of 1 km for not less than 90 percent of the planet, plus nested high-resolution frames with resolution of order 100 m for selected regions. In addition, orbiting spacecraft should carry instruments of the types listed in table XXV to investigate other aspects of the planet discussed in the text.

TABLE XXV.- CANDIDATE INSTRUMENTS - VENUS ORBITERS

[Exclusive of radar mapping instruments]

Instrument	Mass, kg	Volume × 10^3 cm^3	Power, W
UV spectrometer	2.7	3.5	0.9
IR spectrometer	3.0	4.1	2.0
Imager	4.1	7.4	3.5
Neutral mass spectrometer	2.2	3.0	7.9
Charged-particle mass spectrometer	1.3	1.8	1.5
Electron temperature probe	1.3	1.5	2.0
Retarding potential analyzer	2.2	2.7	2.8
Electric field detector	0.5	0.5	0.6
Swept frequency sounder	17.0	2.0	20.0
Cloud photopolarimeter	4.1	6.9	3.2

Radar imaging missions (VOIR) utilizing Mariner spacecraft have been rather thoroughly analyzed (refs. 110, 111, 115-117), and there is little doubt that such a mission can fulfill the data requirements. Weight and power capabilities of Mariner may also permit an array of other experiments.

Open to question, however, is the feasibility of radar imaging systems utilizing Pioneer spacecraft. Preliminary studies (albeit extremely cursory) indicate that such systems might be possible. As such, a less costly Pioneer mission could be an attractive alternate to a Mariner VOIC mission. At least two problem areas can be identified for Pioneer imaging radar systems:

(1) System development: extensive design and development of a system compatible with the engineering constraints of a spinning spacecraft are required.

(2) On-board data compression and/or first-stage data reduction: imaging systems require both high data rate and high storage capacities, which exceed current Pioneer capabilities; means of data compression and/or onboard data reduction are required.

It is recommended that these two areas be examined to fully assess the feasibility of Pioneer-class imaging systems.

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7.0 ENTRY PROBES

Entry probe missions are defined here as those in which probes enter the atmosphere, initially at high speeds, and traverse its full depth making primarily in-situ measurements, although remote observations of the planet surface or atmosphere are not arbitrarily ruled out. However, the probe is primarily an atmospheric sensing instrument, and its two strengths are that (1) by making direct and sometimes simple measurements, it can definitively resolve questions which, when examined remotely, require recourse to complex analytical modeling, often with an attendant lack of uniqueness and certainty and (2) it traverses the full depth of the atmosphere and thus can define the variations of key properties with altitude. In this last connection, however, since the vehicle speed is high at the highest altitudes, one must identify measurement techniques suitable to such speeds to capitalize on the entry probe transit of these altitudes. We will examine ways of responding to or circumventing this limitation.

For purposes of organization, the atmospheric properties to which probe experiments can be addressed are classified as:

(1) Thermal structure: profiles of atmospheric temperature, pressure, and density with altitude

(2) Composition: major species, trace species, isotopes, condensibles, and dust, in the lower and upper atmospheres

(3) Clouds: altitudes of occurrence, morphology, composition, particle size and number density, optical properties, formation processes, transport effects, precipitation, and electrification

(4) Circulation: patterns, horizontal and vertical velocities, altitude regimes, driving mechanisms, energy transport, chemical transport, interaction with thermal structure

(5) Energy balance: planetary and atmospheric thermal radiation, solar radiation, role of clouds and dust, convective transport

(6) Mixing: diffusive, turbulent, turbopause location, effects on CO, O_2, H_2O, HCl, HF, H_2SO_4, etc. abundances, effects on cloud morphology and altitudes, interrelation with circulation and with measured turbulence intensities

(7) Upper atmospheric chemistry: photochemistry, collision chemistry, catalysis, reaction routes, energetics, role of transport

Pioneer Venus has investigations in each of these areas. A key consideration is the degree to which each will be definitive. A clear limitation of Pioneer Venus, and every other spacecraft mission, is that it cannot investigate all properties everywhere. Thus, the four probes of this mission will be clustered within a 60° central angle about the sub-Earth point. Mission constraints thus prevent probes from being sent to the polar regions, to the

subsolar region, and to the afternoon or pre-midnight quadrants of the planet. Polar and subsolar investigations, in particular, will be of great importance to the definition and understanding of the atmospheric circulation and energy balance.

A second limitation of Pioneer Venus, chosen by design, is that the bulk of the entry-probe data will be taken below an altitude of about 67 km, that is, below the cloud tops and in the lower atmosphere. Upper-atmospheric processes will be investigated both by remote sensing and in-situ instruments on the orbiter, and by means of neutral and ion mass spectrometers on the probe bus as it enters the atmosphere to a survival limit estimated to be about 135 km. Thus, the region between 67 and 135 km (100 to 10^{-5} mb) will be investigated by only one in-situ experiment, the upper-atmosphere structure measurement based on accelerometry (LAS, SAS), and by remote sensing from the orbiter.

Future probe missions can thus extend the foundation of knowledge to be laid by Pioneer Venus by (a) carrying instruments not in the 1978 payload, to respond to fundamental questions not addressed by that payload; (b) carrying instruments of a type in the 1978 payload, but of significantly advanced capability, to respond to questions not expected to be definitively resolved; (c) visiting sites on the planet which are important to a complete picture of the atmosphere and its processes, but which are not accessible to Pioneer Venus; and (d) making measurements in the altitude regime above 65 km, which will not be thoroughly explored by Pioneer Venus.

As a necessary prelude to selecting mission goals and candidate payloads for future probe missions, we must discuss in greater depth than given in sections 4.0 and 5.0 the anticipated first-order gaps in knowledge existing after Pioneer Venus in each of the above listed categories of investigation, to which future probe missions can respond.

7.1 Scientific Questions for Advanced Probe Missions

7.1.1 Thermal structure - The primary gaps in a definition of the thermal structure of the atmosphere of Venus expected to remain after the 1978 mission are the lack of measurements at key unexplored locations and the marginal definition of thermal contrasts above 65-km altitude, the altitude regime of the four-day circulation.

Locations of greatest interest and importance for which no data will be returned by Pioneer Venus are the subsolar and polar regions. The subsolar region is the driving center of the general circulation, and it is the consensus of the Pioneer Venus Science Steering Group and the current authors that its unavailability in that opportunity is unfortunate. Comparative data for the subsolar region, the night side, and one polar region would probably be the optimum choice for resolving the questions of thermal contrast in the atmosphere available to drive the circulation, and, in particular, of the vertical distribution of these contrasts. The definition of both the thermal structure of the atmosphere of Venus and the coupling of the thermal structure to the circulation will remain incomplete until these regions are explored,

and the determination of how well the general circulation is defined from the more limited planetary coverage available to Pioneer Venus will not be known until the Pioneer Venus data are received and studied.

The upper-atmosphere temperatures, from 65 km to perhaps 175 km, will be defined by the Pioneer Venus accelerometry (LAS, SAS) to an accuracy of a few °K and the upper atmospheric pressure and density to within a few percent (ref. 118). These measurements will vastly extend our present knowledge of this altitude regime. However, to balance the forces in the upper-atmospheric circulation, Leovy (ref. 119) has shown that the temperature differences need be only a few degrees from equator to pole. Hence, the Pioneer Venus experiment may not be precise enough to establish these differences, particularly since it will be limited to an extreme latitude of 50°.

7.1.2 Composition - The two most conspicuous deficiencies in the Pioneer Venus composition experiments are the altitude gap, from 67 to 135 km, where no *in-situ* composition measurements will be attempted and the lack of a cloud droplet or particle composition experiment.

The altitude gap is in the region of planetary photochemistry, diffusive separation, and processes related to the escape of light gases. Some of the outstanding puzzles of this region of the Venusian atmosphere may be addressed by Pioneer Venus remote sensing from the orbiter, but are not assured of final definition. These include the identification of the source of the ultraviolet haze photographed by Mariner 10, which lies above the main clouds and above the descent phase of the entry probes; confirmation that the apparent motion of these clouds reflects the upper-atmospheric circulation; resolution of the CO underabundance problem (which of the proposed mechanisms correctly explains the rapid loss rates of the products of CO_2 photodissociation?); definition of the turbulent mixing efficiency (is it Earth-like or orders of magnitude greater?); location of the turbopause by *in-situ* composition measurements; and measurement of free radical concentrations that catalyze the upper-atmospheric chemistry. The understanding of some of these matters will likely be advanced by Pioneer Venus remote sensing, although it must be recognized that these questions exist in the face of basically similar remote sensing performed on earlier Mariner missions. In addition, however, the Pioneer Venus bus mass spectrometer could identify some of the free radicals of interest, and it may locate the turbopause, or at least bound it (since the bus is not expected to survive below about 135 km altitude). Photochemical reactions peak between 70 and 100 km altitude, and *in-situ* measurements in this altitude region may be necessary to define adequately the reactions governing the upper atmosphere.

Cloud composition inferences likely will be available from the Pioneer Venus mass spectrometer, but they will be limited to detection of volatile vapors in the cloud layers and below; that is, there is no direct analysis of cloud material. Thus, there is no certainty that the riddle of the Venus cloud composition will be fully resolved. This question has been the subject of speculation for over 200 years, and has now come to focus on concentrated sulfuric acid as the prime candidate (ref. 52).

An analysis of vapor pressure data available for concentrated sulfuric acid solutions (ref. 120) gives the SO_3 concentrations as a function of

altitude shown in figure 36 (wherein it is assumed that the atmosphere in the cloud layers is in vapor equilibrium with the droplets). Even for very concentrated acid (86 to 98 percent H_2SO_4), vapor mole fractions are in the 10^{-7} to 10^{-5} range at altitudes from 55 to 45 km, but rise to the order of 10^{-3} at 30 km. These concentrated acid vapors would be detectable at altitudes up to 50 km by the Pioneer Venus LNMS if it achieves its expected dynamic range of 10^7, but not by the LGC in its samples taken at 53 and 44 km. (The third gas chromatograph sample, at 24 km, is likely below the clouds, but could surely detect SO_3 in vapor equilibrium if acid clouds were present at that altitude and temperature (575° K).) Detection of H_2SO_4 clouds at altitudes above 55 km is in doubt, and the measurement altitude range shrinks with decreasing acid concentration.

Water vapor detection in either water clouds or acid clouds is probably assured. Water clouds in vapor equilibrium produce high vapor mole fractions (fig. 37). Below an altitude of about 58 km, the quantity of water vapor which the atmosphere can hold becomes so large that water clouds at these altitudes would soon evaporate, unless replenished by transport downward from a higher altitude condensation region. Acid clouds also have readily detectable water vapor fractions. (This results from the high ratio of H_2O/SO_3 in the vapor, above sulfuric acid solutions, of the order of 400 even for a concentration of 89 percent H_2SO_4.) The LNMS will be well baked out before flight, so these water concentrations should be seen.

Figure 37 carries an interesting implication relative to acid concentration in the clouds. If these clouds exist, they could be found to display increasing acid concentration with decreasing altitude since the water vapor released can be held in the atmosphere to produce more concentrated acid in the cloud droplets.

The detectability of mercury vapor from clouds of condensed mercury is examined in figure 38. Such clouds would be detectable from vapor measurements by the LNMS over essentially the entire depth presently believed to be cloud-filled on Venus.

What then is lacking in cloud composition determination? Primarily, it is the analysis of solid particulates; the detection of acid clouds of lower concentrations then those shown; and the analysis of acid clouds at altitudes above about 50-km altitude. Put more generally, the cloud composition may not be determined above 50 km if the clouds are H_2SO_4, and will not be determined wherever "permanent" solids (low vapor pressure constituents) predominate.

These limitations could be overcome by providing an alternate sampling inlet route for analyzing droplets and solids in a mass spectrometer, in which the particles or droplets are collected on a filtering surface, and then periodically vaporized by a laser pulse, a spark, or other energy source.

The important role that the clouds play in atmospheric processes, in determining the deposition altitudes of the solar heating and in serving as energy sources and sinks (for condensible materials), makes it mandatory that their chemical nature be understood. Furthermore, if the clouds do <u>not</u> include layers with appreciable abundances of higher-temperature volatiles,

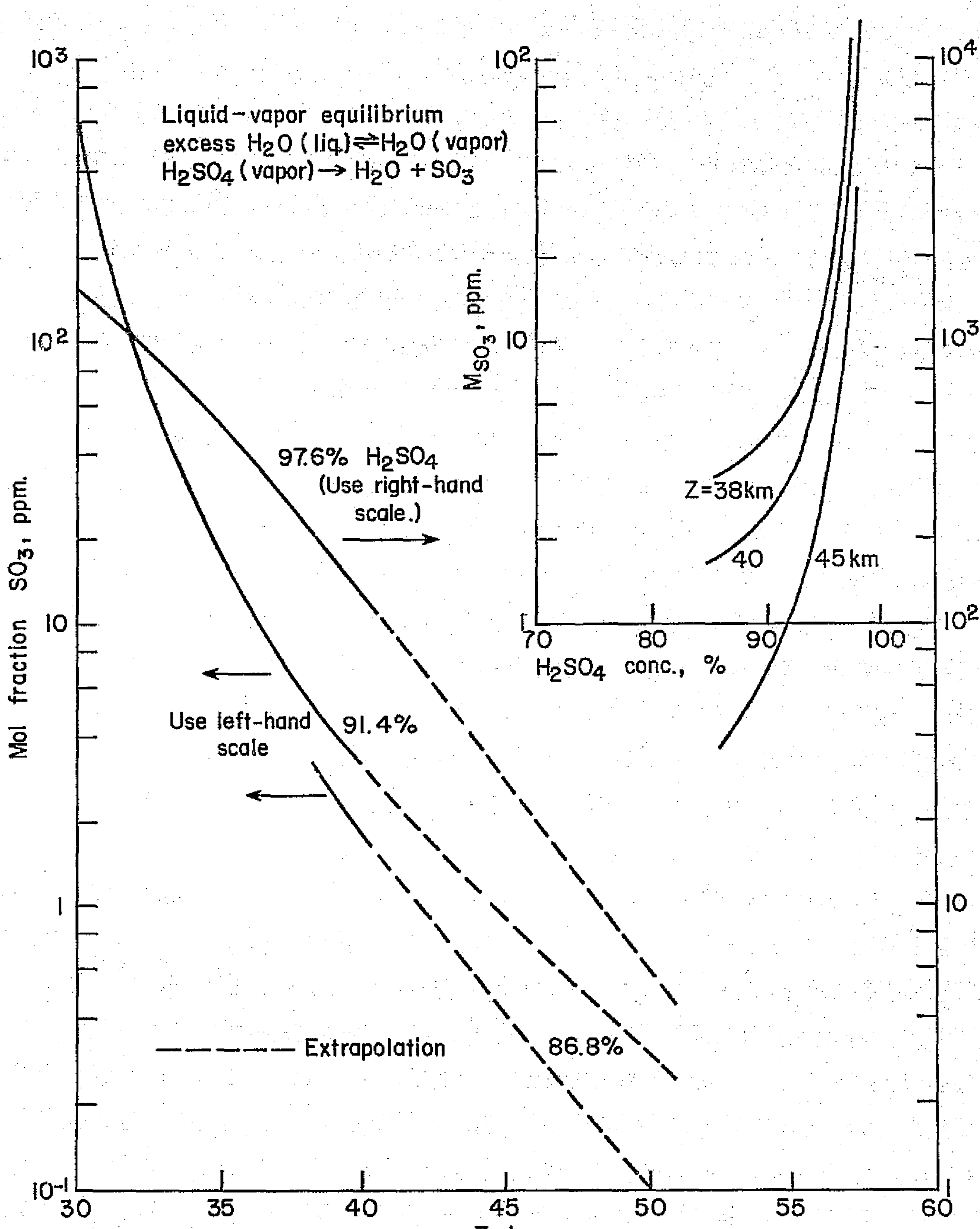

Figure 36.- Mole fractions of SO_3 in the presence of H_2SO_4 clouds.

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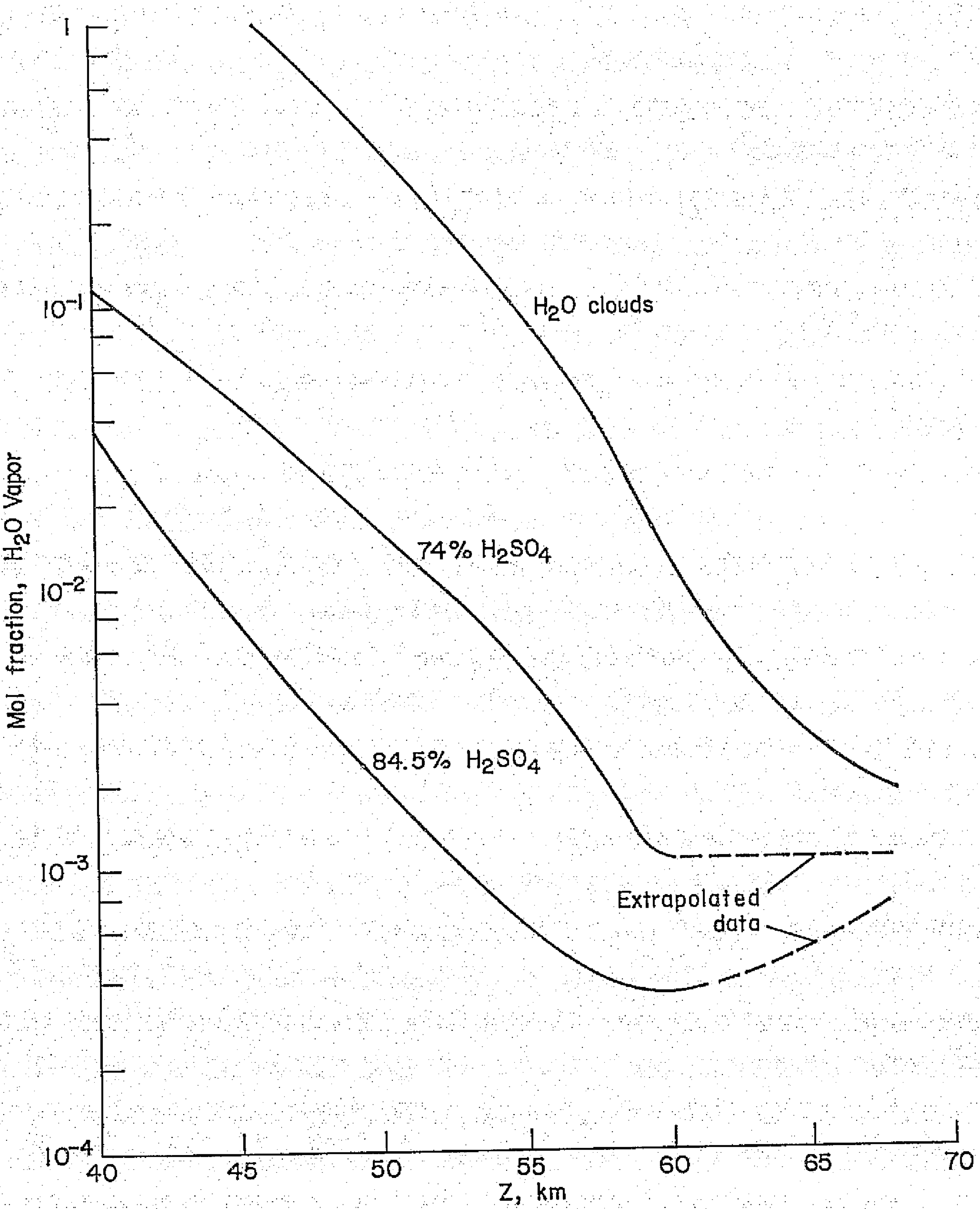

Figure 37.- Water vapor fractions in water clouds and H_2SO_4 clouds.

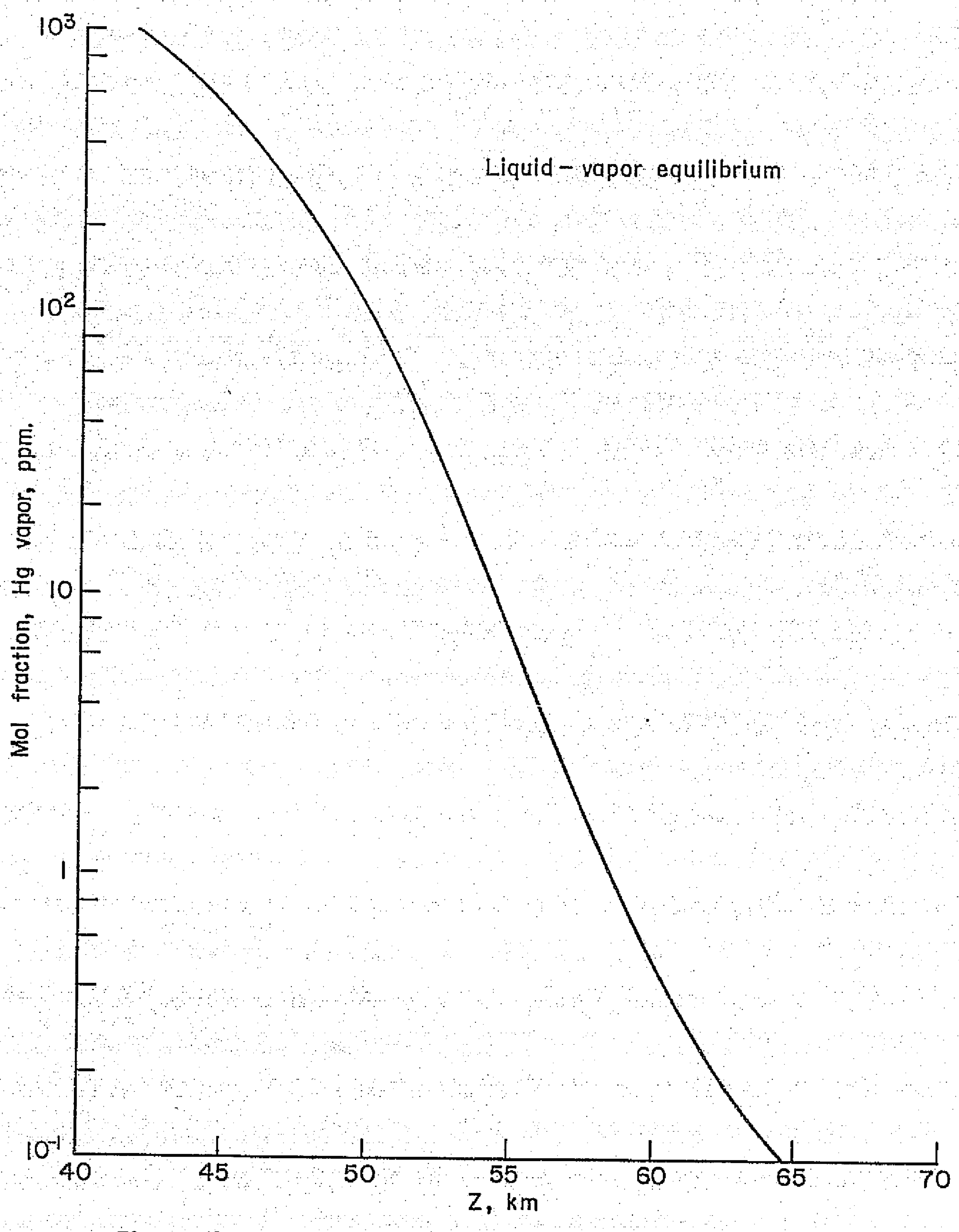

Figure 38.- Mercury vapor fractions in the atmosphere in the presence of mercury clouds.

as suggested by Lewis (ref. 121), this could have important implications for the composition of the planet's crust.

The detection of organic molecules and life precursor molecules in the upper atmosphere is a subject of great interest to biologists. While life as we know it cannot be sustained in the Venus lower atmosphere because of the high temperatures, prebiologic organic molecules might be present. Indeed, at the cloud layers, it is not inconceivable that organisms could survive, supported by the vertical flows that support the cloud droplets. Clouds of concentrated sulfuric acid, or other reactive chemicals, would presumably be unfavorable for life, not only by reacting chemically with them but also by dehydrating, but the adaptability of living organisms to hostile environments on Earth has proved to be remarkable. The water-vapor concentration is a key consideration in forming organics, as a source of hydrogen. The absence of excess oxygen is also a requirement from a thermodynamic equilibrium point of view. Dayhoff et al. (ref. 122) calculate that equilibrium concentrations of species such as CH_4 (10^{-2}), ethane (10^{-9}), formic acid (10^{-10}), and methanol (10^{-12}) occur at 500° K, 200 mb pressure, just to the reducing side of a pure mixture of CO_2 and H_2O. Consistent with Lewis (ref. 121), they find that these mole fractions decrease drastically as excess hydrogen and carbon disappear. (Lewis calculated equilibrium fractions of methane and ethane to be 10^{-8} and 10^{-14}, respectively.) Since methane has not been detected spectroscopically in the Venusian atmosphere, it seems evident that it cannot be present in mole fractions as large as 10^{-2}, and hence that the reducing conditions necessary for equilibrium formation of organics do not occur at Venus.

Of course, the processes shown in laboratory experiments to result in measurable concentrations of these and other more complex organic molecules are not ambient equilibrium processes, but involve electric discharge, photochemistry, or other means to introduce energy, high temperature, and pressure. And it is clear that life and atmospheric methane exist on Earth in the presence of excess oxygen. The equilibrium concentrations suggest, however, that very sensitive instruments would be needed to detect the species listed above. Only the simplest molecules may occur in concentrations detectable by the LNMS. The desirability of carrying more complex instrumentation, such as a gas chromatograph coupled with a mass spectrometer, to detect these species is clearly debatable. Perhaps the best course is to wait for the analyses from the LNMS on Pioneer Venus, with its dynamic range of 10^7, its operating mode in which CO_2 is purged from the sample, and its mass range to 208 amu, to see whether any organics are detected that would encourage further efforts.

Another desirable, but difficult composition experiment is an analysis of volcanic emission gases. The important role played by volcanic emissions in injecting species into planetary atmospheres is well known (ref. 123) and an analysis of volcanic gases for Venus would be of very great interest. The entry probe mass spectrometer is, without modification, suitable for their analysis, but the problem of putting the instrument near enough to an active volcano to measure the gases is probably too much to attempt in remote space missions. Conceivably, in the years ahead, microwave measurements will identify the presence of likely volcanic sites, but even so, it would require unattainable guidance accuracy to put an entry probe within measuring range (a few hundred meters) of such sites. A more promising alternative may be to

use radio measurements onboard balloons to identify active volcanic sites from ground temperature measurements and to deploy dropsondes to sense the gas composition.

7.1.3 Clouds - Pioneer Venus will obtain measurements related to cloud opacities at visible and infrared wavelengths, vertical cloud distributions, backscattering cross sections, particle size distributions for particle sizes mainly greater than 1 μm, shape parameters for the larger particles, temperature and pressure within cloud layers, and the identification of some condensible species present in the atmosphere within and below the cloud levels.

These measurements will extend our understanding of the Venusian clouds, but some of them may, because of instrument limitations, fall short of being definitive. For example, the particle size spectrometer (LCPS) has been modified to detect particles smaller than 1 μm, but this requires detecting a 5-percent current loss on a single detection element. The best current information places the size range of the upper Venusian cloud droplets near 1 μm. The backscattering nephelometer (LN, SN) measures scattering cross section, but does not distinguish between a high density of small particles and a lower density of somewhat larger particles. The limitations in the planned measurements of cloud composition were discussed above.

Future probe missions could obtain a more complete and quantitative description of the clouds including particle composition, particle size, and number density as functions of altitude. It seems both possible and desirable to develop and fly instruments capable of this. In addition, further measurements on the optical and thermal properties of the clouds may be needed (see Energy Balance discussion below). Significant additional questions not specifically addressed by the 1978 mission include: transport characteristics of the clouds for energy and atmospheric species; energy sources and sinks associated with condensation processes in clouds, and condensation-precipitation cycles. On Earth, the water condensation-precipitation cycle has a major thermal effect on the atmosphere. It is accompanied by the development of electric fields and lightning discharges invariably associated with precipitation (ref. 124). It has, in fact, been argued that electrostatic fields in thunderstorms are the dominant mechanism for droplet growth-producing precipitation (ref. 125). Thus, on Venus, the presence of electric fields in clouds could be an important diagnostic for determining if similar processes are active there and for identifying altitudes of droplet growth. The detection of sferics emanating from lightning discharges would constitute strong evidence for precipitation on Venus. Other techniques for investigating condensation-precipitation phenomena should also be considered.

7.1.4 Circulation - Pioneer Venus will give a first-order view of the Venusian atmospheric circulation, but, because of the discrete number of measuring sites (4), because of the limitation to the region within 60° central angle of the sub-Earth point, and because of the possibility of local flow anomalies, the global functional dependence will remain uncertain and will at best require gross extrapolation and interpolation. Similarly, temperature contrasts will be defined between the accessible entry sites, but the horizontal resolution is poor, and the horizontal gradients may be nonlinear, so the driving mechanisms for the winds may not be established in any but a gross

sense and not globally. In addition, such interesting features as the interaction of the flow with the subsolar region and the subsolar and polar regions themselves will not be investigated under the present restrictions on probe targeting.

To elaborate, such first-order questions as the basic pattern of flow may remain in doubt. There is the perrenial question of the Venusian atmospheric circulation (probably oversimplified): is the circulation symmetrical about the subsolar-antisolar axis or is it distorted to include an equatorial-polar component? Surprisingly, the Mariner-10 results (ref. 69) as well as the Venera data (ref. 70) and Earth-based UV and spectroscopic observations (e.g., ref. 72) show that the basic pattern is almost purely zonal, at least above the clouds. The question remains: what is the relationship of this to the lower-atmospheric circulation? Furthermore, it is still important to determine if the circulation, which remains after the mean zonal flow is subtracted, is essentially solar-antisolar or equator-polar. A polar probe should be capable of answering the latter question, that is, it would experience winds toward the darkened hemisphere, or significant downflow, depending on which of the above simplified models governs. The actual case, of course, is likely to be a complex blending of these tendencies, but the polar probe would show this also.

Since it would take a very large number of probes to obtain adequate horizontal resolution, the objective of future probe missions should be to reach interesting areas, such as the subsolar and polar regions. In addition, future probes should probably be capable of investigating local gradients, perhaps through use of miniprobes released from the main probe. In this way, a rather detailed picture of the given region could be obtained, and if the regions to be investigated are chosen carefully, valuable insight into the form and driving mechanisms of the circulation could be obtained.

7.1.5 Energy balance - If the three energy balance experiments (LSFR, LIR, SNFR) of the Pioneer Venus mission do not encounter major unforeseen difficulties, they should do a great deal toward establishing the energy deposition profiles of the Venusian atmosphere for large solar zenith angles (greater than 55°). These experiments are subject to some limitations, however, such as the lack of flatness of the spectral response in the solar radiometers, the possible presence in the atmosphere of presently unknown absorbers that can interfere with cloud absorption measurements, and possible interference in the net flux measurement by convective heating of the sensor. Hence it is not presently clear how definitive these measurements will be.

The effect of the large solar zenith angles is to make the interpretation of the solar flux measurements model-dependent. Thus, there are good reasons to want improved global coverage for the measurements, and the subsolar location is particularly attractive. A measurement to define the albedo of the planet surface in the visible is desirable, although the LSFR instrument may produce some information on this since the value inferred from Venera 8 is 0.6 or greater (ref. 126), generally regarded as unrealistically high.

7.1.6 Mixing and upper-atmospheric chemistry - As discussed in sections 3.0 and 6.0, the photochemical stability of the carbon dioxide in the

atmospheres of Venus and Mars has attracted widespread theoretical interest in recent years. The altitude for maximum photodissociation is, for Venus, near 70 km (ref. 127), but very significant dissociation occurs at all altitudes from the cloud tops to above 100 km. Since photochemical activity apparently peaks at altitudes below the turbopause, vertical convective transport (i.e., turbulent mixing) plays an important role in these processes and in the vertical distributions of CO and O_2, as well as HCl, HF, and molecules containing sulfur.

Explanations for the photochemical stability now center around catalytic reactions that speed the recombination of CO and O_2. However, at least two kinds of catalysts are advanced, those derived from water (OH, HO_2) (ref. 127) and those involving chlorine compounds (ClO, ClOO) (ref. 56) and correspondingly different reaction routes. The resolution of these alternatives is desirable. If chlorine is present in sufficient concentrations, its effect would be about a factor of 10 more important than the hydrogen radicals.

The intensity of the turbulent mixing processes on Venus is an important aspect of the planetary physics, governing matters of species abundance and vertical distribution as well as the altitude where diffusive separation begins. There have been some indications that turbulent mixing is very vigorous on Venus, leading to eddy diffusion coefficients 100 to 1000 times those ascribed to the Earth's atmosphere. This high level of mixing is qualitatively supported by measurements of the turbulence, from scintillations in phase and strength of the radio signals obtained during occultations of Mariners 5 and 10 (ref. 74), and also by the high vertical flow velocities derived from data from Veneras 4 through 8 (refs. 21 and 128), and by the pictures showing patterns typical of convection cells in the UV cloud features (ref. 69). However, it is not possible to connect quantitatively the measured turbulence and velocity data with an eddy diffusion coefficient, which probably is a function of altitude.

In a recent paper, Prinn (ref. 58) shows that the vertical mass diffusion coefficient can be derived from the scale height for the cloud material density, H_c, the atmospheric gas scale height, H, and the vertical flow velocity. It will therefore be possible to derive a mass diffusion coefficient from the Pioneer Venus experiments on atmosphere structure and cloud particles, provided the cloud number densities and mean particle sizes are established, but in view of the uncertainties, this is regarded as a contributing but not definitive piece of information.

The apparent dryness of the Venusian atmosphere is another feature that has attracted interest. Alternative explanations are available, including low water content at planetary formation (ref. 129); photochemical dissociation with subsequent escape of the atomic hydrogen; and trapping of the water vapor by absorption in hygroscopic cloud droplets (ref. 52). Measurements of the vertical distribution and transport rates of key species would do much to permit the governing mechanisms to be identified.

Other important questions relative to the chemistry of the atmosphere include: Why are no sulfur compounds detected? Why has O_2 not been detected? The first of these questions may be closely related to the question of cloud

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composition. If H_2SO_4 clouds are formed by the photodissociation of COS, SO_2, and H_2S in the upper atmosphere, this could account for the absence of detectable sulfur in the upper atmosphere. By trapping H_2O, the sulfuric-acid clouds might also account for the small amount of detectable water vapor. Thus, the determination of the composition of the upper-level clouds will be a very useful adjunct to the considerations of atmospheric chemistry, but it may not be achieved by the 1978 mission.

Rather extensive modelir studies have been done, but until adequate composition data are availab , the key processes will remain speculative. The Pioneer Venus mission will not provide in-situ data for these reactions in the important altitude range, 70 to 100 km. Further, only trace quantities of hydrogen and chlorine compounds (mixing ratios of 10^{-6} typically) are required to cause the observed effects, and the remote sensing from the orbiter may be unable to provide data of sufficient sensitivity in this altitude range.

Future Venus missions therefore should give increased attention to defining both the composition of the upper cloud layers (the UV haze) and to measuring trace species in the altitude range from 70 to 100 km. Important species to measure include H_2O (difficult in the presence of contamination), HCl, COS, and SO_2, O_2, and H_2O_2, and, if possible, Cl, ClO, ClOO, OH, HO_2, and O_3 (Prinn, personal communication, 1975). The use of a mass spectrometer for these measurements is very desirable, if a probe can be slowed adequately at high altitude or if an appropriate sampling procedure can be devised. A shock-layer radiometer experiment is ideally suited to work in this altitude range, but, unfortunately, the sensitivity to detect trace species is inadequate (ref. 118).

Since the measurement of upper-atmospheric free radicals in trace concentrations by a mass spectrometer is difficult, and not presently practiced successfully in the Earth's atmosphere, it is clear that laboratory research to develop suitable instrument techniques is needed before these measurements are undertaken. This effort should be encouraged and supported by NASA. It will pay dividends at all the planets and in the Earth's upper atmosphere.

7.1.7 Subsurface temperature - Entry probes, by virtue of operating below the ionosphere, can detect radio emissions from the planet at wavelengths longer than 300 m, and thus can see into the planet to considerable depth. Little is known of the planetary temperatures or properties at such great depths. However, to interpret the observed emission in terms of temperature would be risky since the dielectric nature of the subsurface is unknown. An added difficulty is that the long wavelengths require proportionately immense antennas. The smallest "directive" antenna (which actually looks up and down simultaneously) is the half-wave dipole, 150-m long, which is obviously impractical. It would be subject to interfering emissions from the ionosphere and from thunderstorms. More directive antennas would be similarly much larger than the probe and therefore unmanageable. Hence although there are interesting results to be obtained in this area, it appears that, for practical reasons, they cannot be achieved by means of entry probes.

7.2 Scientific Objectives for Advanced Probe Missions

The above discussion has identified important scientific questions for understanding the atmosphere of Venus which are not expected to be resolved by the Pioneer Venus mission. Suitably condensed, it leads us to the following set of scientific objectives for future probe missions.

(1) Obtain atmospheric data near subsolar and polar entry sites and possibly in the afternoon or premidnight quadrants. These data are necessary so that the character of the atmosphere is established in regions critical either to driving or to defining the general circulation. The primary emphasis at these sites is on wind velocities and directions, atmosphere structure, local pressure gradients, thermal balance and deposition, and comparative cloud cover (relative to that seen near the morning terminator). However, all of the other measurements taken, for example, concerning the presence of convection cells or the abundance of trace species, will also be of high interest on a comparative basis.

(2) Obtain data in the altitude region essentially inaccessible in situ to Pioneer Venus, above 65 km and below 135 km, relative to the circulation, its driving forces, atmospheric chemistry, and turbulent mixing. The questions of atmospheric photochemistry and species transport are central to understanding the present makeup of the atmosphere as well as how it reached this state, and answers to these questions still will be model-dependent after Pioneer Venus. The circulation seen from Earth and by Mariner 10 lies largely in this altitude regime (it is believed), and Pioneer Venus wind measurements will be largely prevented at these altitudes by a combination of insufficient probe response to the winds and communications blackout. Comparative temperature measurements by the Pioneer Venus probes may not have the required degree of relative accuracy ($\leq 1°$) at these altitudes.

(3) Obtain an improved characterization of the clouds on Venus and their role in determining the atmospheric thermal structure. Key aspects that will require further definition are expected to include composition at upper levels, composition of particulates, particle optical and thermal properties, transport and source and sink characteristics for energy and matter, morphology, and the presence of condensation, precipitation, evaporation cycles, and concommitant electrical phenomena.

7.3 Technological Concepts for Advanced Probe Missions

The feasibility of satisfying the above scientific objectives depends in part on overcoming those technological limitations imposed on Pioneer Venus which restrict it to entry sites around the sub-Earth point and to altitudes below about 65 km, where the probes attain subsonic velocities. In addition, feasibility depends on identifying or developing instruments or probe systems of advanced capability in some instances. If advances in understanding the planet's atmosphere by means of in-situ measurements are to be realized, concepts to overcome these limitations must be identified and must be capable of realistic implementation.

Consider the two primary limitations on Pioneer Venus: the limitations on permissible entry sites and on the measurement altitudes. The entry sites are constrained primarily by two factors: the choice of direct communications to Earth (rather than relay communications to an orbiter) and the injection of the probes onto their planetary entry trajectories from the bus approach trajectory (rather than from orbit). Thus, it is evident that these constraints could be removed or relaxed by the change in the mission mode from a direct entry with direct communications to Earth to an entry from orbit with communications relayed by the orbiter.

Consider the following as one example of how this could be used to make the subsolar point accessible. The orbiter and probes are first put into a highly eccentric orbit (to conserve injection fuel) with periapsis over one of the poles (see fig. 39). At injection, the orbital plane is nearly parallel to the plane of the terminator, for a near-minimum-energy interplanetary transfer, as is evident in figure 39(a). After 56 days in orbit, however, the inertially fixed orbital plane contains the subsolar and antisolar points (fig. 39(a)) and the subsolar probe is launched from the orbiter at apoapsis[2] (fig. 39(b)).

Entries can also be made at the pole that lies under the periapsis, and entries in the afternoon region of the daylight hemisphere may be made at any selected latitude in the time period of 56 days after the subsolar entry.

Venus is near inferior conjunction in the above mission profile at the time the subsolar entry probe enters the atmosphere. Furthermore, subsolar entries will generally occur out of sight of the Earth unless Venus is near superior conjunction. This means that relay communications must be used, and there is no opportunity for DLBI probe-position measurements from Earth. Doppler tracking from the orbiter will yield information on one component of the horizontal wind. Ideally, another tracking platform would be desirable, positioned to measure the other velocity component; or, alternatively, an onboard Doppler radar, measuring probe velocity relative to the planet surface could be used.

To overcome the measurement altitude limitation on Pioneer Venus, there are three possible approaches: (1) Probes of very small mass and large frontal area, or with lifting capability, can be used so that the deceleration occurs high in the atmosphere, and so that the low-speed measurements that are the primary payload of Pioneer Venus can begin at higher altitudes. (2) Small auxiliary packages can be released, injected, or floated to higher altitudes from the decelerated main probe. (3) Experiments able to measure the required parameters during the high-speed phase of the probe entry could be used on normal probes.

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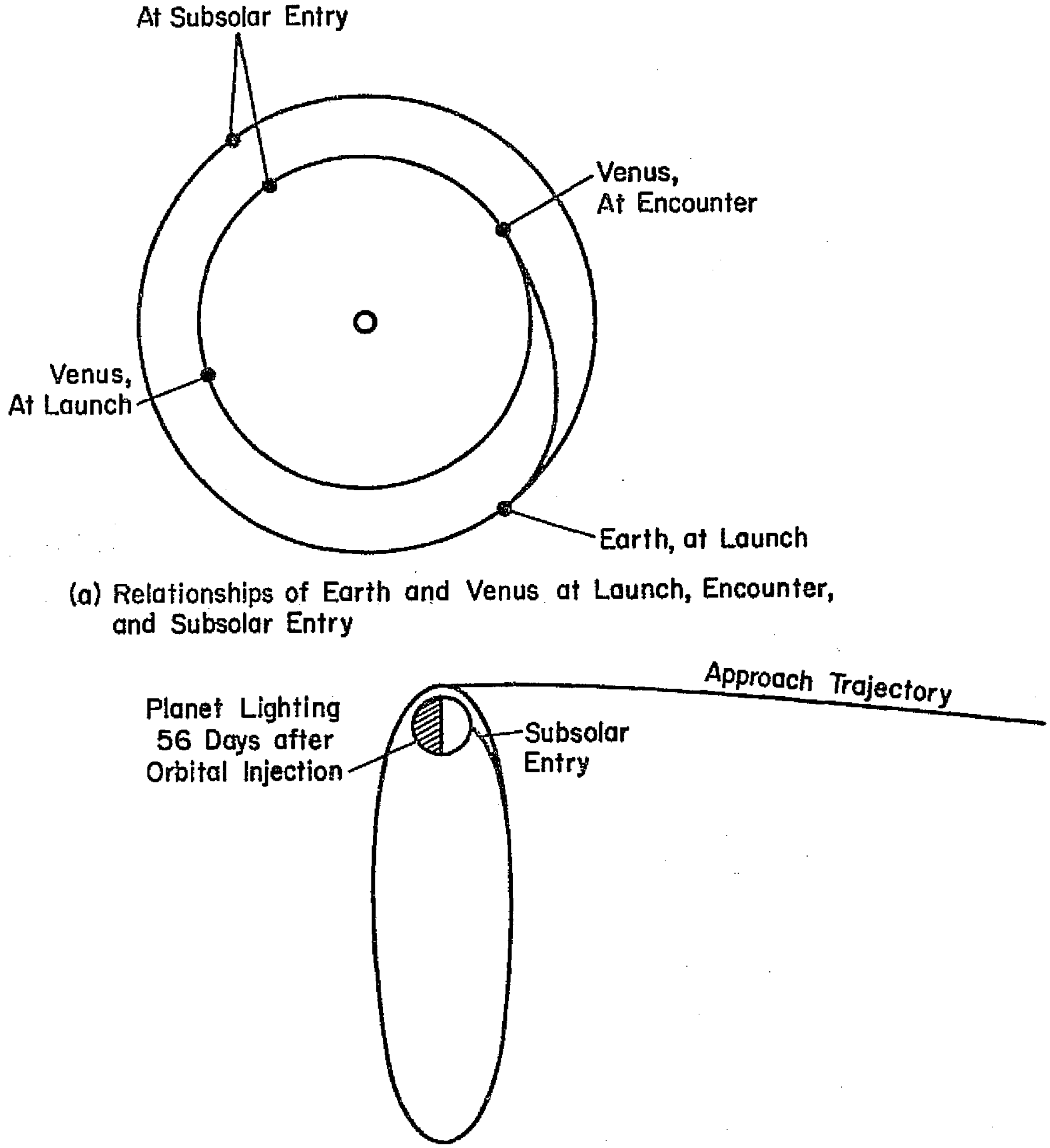
[2]This is not the mission profile selected in a subsequent section since it does not minimize propellant requirements. However, it is retained here since it was the first concept we devised to achieve subsolar entry and it illustrates the basic possibility.



(a) Relationships of Earth and Venus at Launch, Encounter, and Subsolar Entry

(b) Orbit and Descent Trajectory for Subsolar Entry

Figure 39.- Mission design to accommodate subsolar and polar entry probes.

The use of light probes to increase the altitude at which low speeds are reached is an attractive concept. The gains that can be made in this way are shown in figure 40, where the altitude at which the probe decelerates to a Mach number of 1 is plotted as a function of the ratio of probe mass to frontal area, as expressed by the ballistic coefficient, m/C_DA. For the Pioneer Venus probes, the ballistic coefficients (conventionally expressed in English units) are 1.1 to 1.2 slugs/ft^2, consistent with the commencement of the low-speed phase at about 70-km altitude (flight-path angle = 20° at entry into the atmosphere). Lowering the ballistic coefficient by a factor of 10 typically adds about 10 km to the low-speed regime. Thus, at $m/C_DA = 0.1$, altitudes to 81 km are available, while at $m/C_DA = 0.01$, low-speed measurements could be made to an altitude of 90 km. However, there are practical limitations on how low a value of ballistic coefficient can be achieved. For example, increasing the frontal diameter of the Pioneer Venus large probe from 1.45 to 4.6 m while holding the weight fixed would be required to obtain a factor of 10 reduction. Such a modification might be possible, but it would be difficult. Further reductions in m/C_DA almost certainly would require that the probe capability be curtailed, for example, to the use of only very light sensors such as transponders, pressure and temperature sensors, and accelerometers, while heavy instruments such as mass spectrometers could not be accommodated. Therefore, this approach does not provide the desired high-altitude capability in more than a very limited sense.

Other possible concepts include entry at very shallow flight-path angles, and the use of aerodynamic lift, both of which will tend to decelerate the probe at higher altitudes (fig. 41). The minimum entry-path angle that can be chosen without skipping upward out of the atmosphere and escaping back into space is between -7° and -8°, and a case is shown for entry of a lightweight probe with zero lift at -8° path angle. It still passes through $M = 1$ at an altitude of 82 km, comparable to the steeper entries in figure 40, but over much of the entry it hovers near 100 km.

Entries in which aerodynamic lift is used have a very interesting characteristic if the entry-path angle is <u>not</u> too shallow. Two such cases are shown in the figure, for initial path angles of -12° and -18°, and lift/drag ratios of 0.3 to 0.5, constant over the entry. Blunt configurations capable of generating this moderate amount of lift are known from past theoretical research and tests in ground facilities (refs. 130-132). The trajectories with lift exhibit an initial period of deceleration at nearly constant altitude, in which about 2/3 of the entry velocity is lost; they then enter into a zoom-climb maneuver in which kinetic energy is exchanged for potential energy to attain a peak altitude above 175 km, from which they descend with velocities always below 4 km/sec. These trajectories offer the important capability to explore the upper atmosphere of Venus very much in the fashion of sounding rockets, but require instruments capable of working in the speed range to 4 km/sec.

The distinction between 4 km/sec and 11.6 km/sec (entry velocity) for instrument purposes is very significant. Stagnation temperatures attained by the flow, if brought to rest, for conditions along the highest zoom-climb trajectory in figure 41 are 1500° to 2600° K, far below the 8000° peak

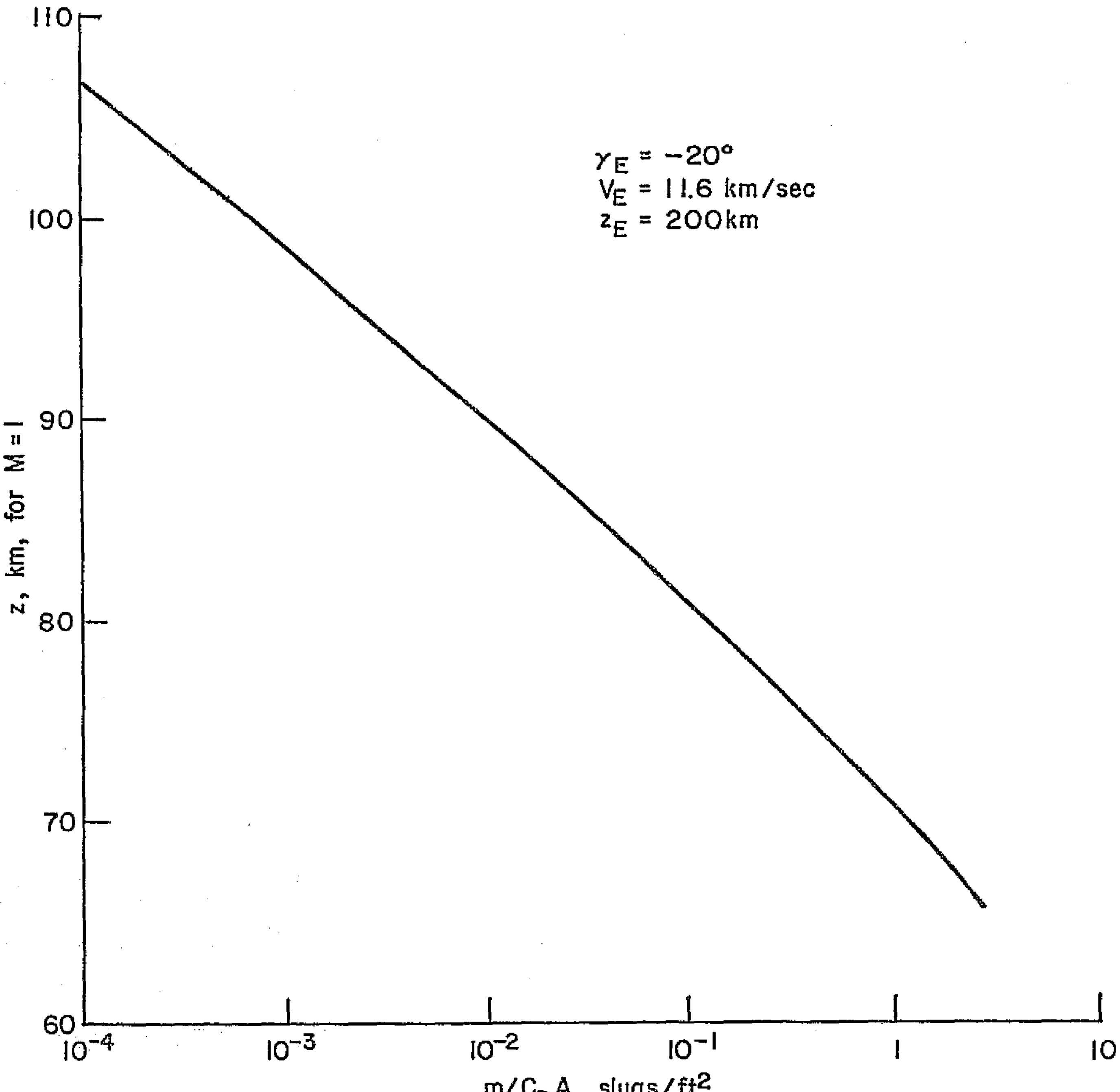


Figure 40.- Effect cf lightweight probe design on altitude for M = 1.

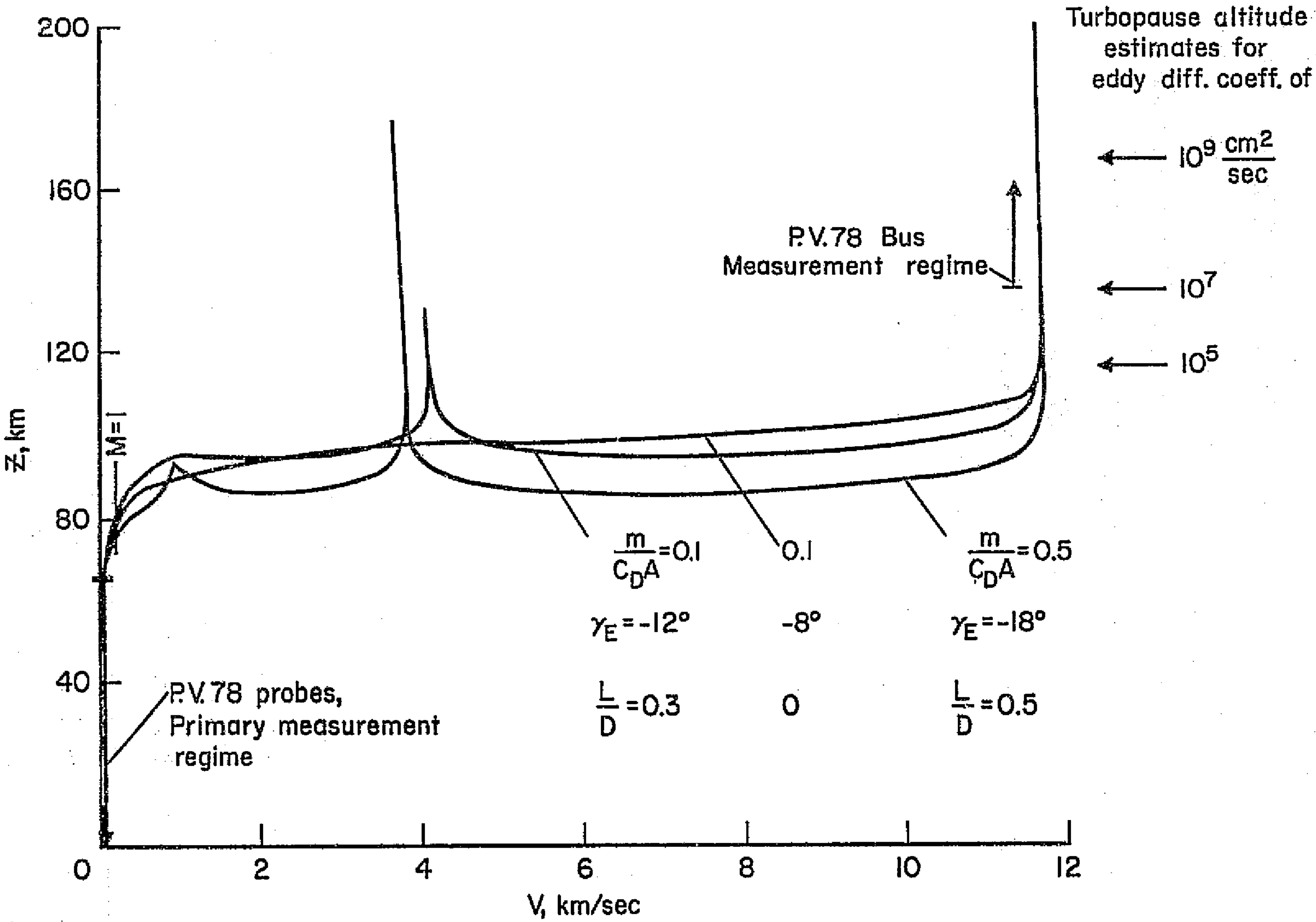


Figure 41.- Trajectories for grazing entry and trajectories incorporating aerodynamic lift.

encountered on first passage through these altitudes. As a result, the flow is negligibly ionized, and radio communication and tracking are maintained. Chemical reactions of the atmospheric species could, of course, occur at equilibrium at these temperatures. For example, the equilibrium degree of dissociation of the atmospheric CO_2 (a weakly bonded molecule) is about 40 percent. However, the gases experience few collisions at these altitudes, so that equilibrium is not attained in the shock layer. Furthermore, the flow is not necessarily brought to rest before mass analysis, but may be admitted to the mass spectrometer with the streamlines aligned with the ion injection axis, so that the stream velocity is used instead of accelerating potentials to inject the ion beam. A mass spectrometer designed and installed in this way should be able to perform in-situ analysis of the unperturbed atmosphere. Finally, probes of this design will exhibit measurable responses to the wind to very high altitudes. Response in horizontal velocity should be detectable to at least a 90-km altitude, while responses in vehicle flight attitude (which is rotated by the presence of wind) may extend to 150 km. (The latter are measurable by means of gyroscopes.) Hence it would appear that a technological concept permitting measurements in the altitude regime above 65 km is identified.

Before leaving these considerations, however, it will be useful to review briefly the capabilities of three other alternatives: (1) high-altitude balloons, (2) subprobes of very low m/C_DA, and (3) sounding rockets launched from entry probes. The high-altitude balloon proves to be incapable of reaching the desired altitudes. A thin mylar balloon filled with hydrogen can barely lift its own weight to a 100-km altitude. The low m/C_DA subprobe is, in effect, the option discussed earlier, with very limited payload capability, as shown in figure 40, and it does not match the altitude capability of the zoom-climb lifting probe. The rocket-propelled sounding rocket appears to offer real possibilities. Rough estimates indicate that a sounding rocket launched upward from a probe at an altitude of 65 km could, for 45-kg all-up weight, carry a 12-kg payload to a 120-km altitude. The advantage offered is lower speeds at the highest altitudes (zero, ideally), while the disadvantage is the greater system complexity and smaller instrument payloads. Nevertheless, the sounding-rocket option should be considered an available technique for the upper atmospheres of Venus and other planets.

7.4 Recommended Mission

Given the scientific objectives and technological concepts of the two preceding sections, what are the recommended post-Pioneer Venus probe missions? They are of two types, but possibly they can be combined. The first type is probes launched from orbiters to explore the subsolar region, the polar region, and the afternoon and premidnight quadrants of the planet's atmosphere. These respond directly to objective 1 in section 7.2 and, given some instrumentation developments, they can respond to objective 3, improved cloud characterization. The second type is probes to explore the neglected altitude region from 65 to 135 km, objective 2. If one of these latter probes is launched from an orbiter to the subsolar or polar region, the objectives are combined. Alternatively, the high-altitude experiments could be performed by direct entries centered around the morning terminator, as a direct follow-up to Pioneer

Venus. They would, however, give lower overall return if so targeted, by leaving the critically interesting subsolar and polar sites uninvestigated.

We postulate a class of possible post-Pioneer Venus missions that are multiprobe. If modeled closely after the 1978 design, they would consist of one large probe and three small probes. However, other combinations prove to be more attractive for satisfying the scientific objectives we have discussed, in particular, one consisting of a lifting, high-altitude large probe and two nonlifting small probes. The large probe is the subsolar probe. It enters the atmosphere at a moderately shallow angle near 15°, zoom climbs above 150 km, and deploys its instruments just below 4 km/sec. It then descends to and through the clouds into the lower atmosphere, collecting data for comparison with the 1978 probes. One of the small probes is targeted to that polar region most accessible to the orbiter, while the second small probe is targeted to the afternoon or premidnight quadrants of the planet. (The scientific advantages to be weighed in making this latter choice have not been fully evaluated at present.) The small probes, in order to remain capable of accommodation by a single orbiter, are limited to small payloads, but somewhat larger than those on the Pioneer Venus small probes. The three probes are not sent into the atmosphere simultaneously, but are held on the orbiter until the entry sites chosen become accessible. The lack of simultaneity is perhaps a disadvantage, but it is believed to be not crucial because of the nature of the information being acquired, and because of the slow rotation of the planet, the long thermal response times of the lower atmosphere, and the resultant lack of diurnal and seasonal variations in the atmosphere.

Consistent with our recommendation in section 2.2 that all future entry probe missions should carry landed science, the three probes of this mission are sized to include landed soil composition measurements, soil hardness, short-term seismicity, and wind velocity.

7.4.1 Instruments and instrument research to satisfy science objectives - The main areas in which instrumentation must be advanced are in the determination of cloud particle composition, cloud characterization, and atmospheric composition measurement, including free radicals, at higher flight velocities. It cannot be our present purpose to solve these instrumentation problems, but some conceptual approaches can be indicated. It is clear that research is needed in these areas to develop such conceptual suggestions into real possibilities. This research will support not only instruments needed for future Venus probe missions, but also Jupiter probe missions and Earth atmospheric research.

To measure the composition of condensible clouds, it seems possible to place a filter in a sample collecting duct and to periodically heat it to above the vaporization temperatures of candidate condensibles while simultaneously admitting a gas sample to a mass spectrometer. To apply this approach to "permanent" solids (dust) with a high vaporization temperature suggests that heating to vaporize the solids should be performed by a laser pulse. Other alternatives to particle analysis include x-ray fluorescence and attenuated total reflectance spectroscopy. Information pertinent to composition could also be derived simply from measurements of dew point, evaporation temperatures, and the latent heat of condensation.

Candidate instruments to extend the expected knowledge of particle size distribution in the clouds include particle impactors, forward-scattering polarization nephelometers, and aureole detectors. The particle impactors are basically piezoelectric crystals that measure droplet mass accumulation by changes in the natural frequency and average momentum by the pulse heights generated by the impacts. For crystals with frequencies in the range of 10^5 Hz, in excess of 10^4 impacts per second can be readily accommodated and, from the measured momentum and mass and knowledge of the descent velocity relative to the atmosphere, the droplet mass (and hence size range) can be redundantly defined. Data-handling electronics must be used to develop the statistics of the impact masses and energies. Instruments of this type have been developed for use in cloud-physics studies on Earth.

The forward-scattering nephelometer has far more capability than the elementary Pioneer Venus instrument. By measuring light diffracted from small droplets in the angle range from 5° to 40°, it detects particle sizes unambiguously. By incorporating polarization sensing, it acquires information on index of refraction of the droplet and hence on its composition. This instrument requires that optics be deployed outside the spacecraft and that multiple mirrors or a movable incident light beam be used. Hence it is more complex to implement than the Pioneer Venus nephelometer, but gives far more definition of the cloud particles. Its design would require careful attention well in advance of flight application.

Instruments to measure electric fields in clouds should not require any major developments, since in the past they have been developed for use in particle-and-field experiments on spacecraft and could be applied to this measurement with some adaptation. Similarly, receivers capable of detecting and characterizing the radio-frequency "static" signals from lightning discharges should be both simple and readily designed and developed.

Sampling the atmosphere to investigate composition at flight speeds to 4 km/sec imposes requirements on the sampling techniques to assure cleanliness or freedom from contamination by the heat shield. Sampling by mass spectrometers at high vehicle speeds is common practice in sounding-rocket research in the Earth's upper atmosphere, under free-molecular flow or slip-flow conditions, but under continuum-flow conditions, expected to occur below 120 km on Venus, the problem is more difficult. One approach capable of producing a clean sample is to admit it through a pitot probe, deployed to a position above the vehicle boundary layer in the flow along the conical sides of the probe after the period of severe aerodynamic heating is over. A deployable pitot probe of this type is planned as a stagnation-pressure measurement inlet on the Pioneer Venus small probes. Contamination by the heat shield of the atmospheric sample entering this tube should not occur, according to boundary-layer theory, since ablation products are confined to a diffusion boundary layer. This arrangement should also be superior to the stagnation-point inlet tube studied recently for outer-planet-probes atmospheric sampling, for technical reasons we will not elaborate here. Validation of high-speed sampling for continuum flow conditions does not seem to pose fundamental problems, but it requires laboratory research to confirm this.

The problems of detecting very small concentrations of free radicals have already been alluded to, and research in this area should be supported, both for planetary and Earth-atmospheric applications. The technique of directing the stream velocity into a mass spectrometer in free molecular flow has received some attention in upper-atmospheric research on Earth, and for the upper-atmosphere mass spectrometer on Viking, but it requires further study, both in analysis of its limitations and in tests in molecular beams or other laboratory apparatus.

7.4.2 Recommended payloads - The recommended payloads are selected to respond to the above discussions of scientific questions and objectives, based on available and predicted instrument capabilities. The problem is not one of identifying a scientifically interesting and valuable payload, but of limiting it to a manageable size. In the absence of fully developed instruments in some categories, it is difficult to estimate weight reliably. Weights given assume that weight minimization will be given important attention, so as to maximize the scientific return from the mission. With these limitations in mind and in the spirit of suggesting a payload to inspire further thought by others (and hopefully instrument developments as well), we propose the payload shown in table XXVI.

TABLE XXVI.- RECOMMENDED PAYLOAD

Instrument	Estimated weight	High altitude and subsolar probe	Polar and afternoon small probes
(1) Thermal structure			
Temperature sensor	0.5 kg	x	x
Pressure sensor	0.5	x	x
Accelerometer			
Three-axis	1.0	x	
Single-axis	0.3		x
		2.0 kg	1.3 kg
(2) Composition			
Mass spectrometer[a]	7.0	x	
		7.0 kg	
(3) Clouds			
Forward-scattering nephelometer	2.0 kg	x	
Backscattering nephelometer	0.7		x
Particle impactor	1.0	x	
Aureole sensor	1.0	x	
Condensimeter-evaporimeter	1.0	x	
Electric-field sensor	0.5	x	x
Sferics detector	0.5	x	x
		6.0 kg	1.7 kg
(4) Circulation			
Transponder	1.0 kg	x	x
Doppler radar and altimeter	4.0	x	

TABLE XXVI.- RECOMMENDED PAYLOAD - Concluded

Instrument	Estimated weight	High altitude and subsolar probe	Polar and afternoon small probes
Three-axis gyroscope attitude sensor	1.5	x	
		6.5 kg	1.0 kg
(5) Energy balance			
Net flux and solar extinction radiometer	1.0	x	x
Solar flux radiometer	1.0	x	
		2.0 kg	1.0 kg
(6) Mixing and upper-atmosphere chemistry			
Mass spectrometer		x	
Turbulence sensors			
Accelerometers		x	x
Radio link analysis		x	x
Atmosphere structure and cloud density instruments		x	x
(7) Landed science			
X-ray fluorescence soil analysis	2.3 kg	x	x
Soil hardness		x	x
Short-term seismicity		x	x
Wind velocity	0.3	x	x
		2.6 kg	2.6 kg
TOTAL INSTRUMENT WEIGHTS		26.1 kg (57.4 lb)	7.6 kg (16.7 lb)

[a]Includes multiple inlets for droplet and particle sampling, continuum gas analysis, and free molecular flow analysis.

Note that no instrument weight charge has been made for mixing and upper atmospheric chemistry since these instrument weights have been counted under other categories. Similarly, organic analysis may be performed by the same mass spectrometer that does the other composition measurements within its limitations on sensitivity.

The landed science also includes two measurements obtained with a multiple-use instrument - the accelerometer, which can be used in a seismometer mode, as it is on Pioneer Venus; and can also be used for impact deceleration, to measure soil hardness. Thus, no instrument weight is shown for these measurements.

The total instrument weight of 41.3 kg (91 lb) may be compared with the total of 35.9 kg (79.1 lb) for the Pioneer Venus probes. Thus, an increase in payload capability (15 percent), which might be expected from the added

efficiency of servicing the advanced-mission instruments from three-probe systems instead of four, is assumed in the above selection. The mission design is predicted on accommodating this payload.

7.5 Engineering Considerations of Recommended Mission

The recommended baseline mission requires the delivery of three probes (one large and two small) by means of an orbiter/bus. The large probe is designed to explore the high-altitude region extending up to about 170 km by means of a lifting zoom-climb maneuver and to perform measurements in the lower atmosphere during terminal descent, and it is targeted to the subsolar region of the planet. One of the small probes is directed to enter in a polar region, and the other small probe is considered here to be directed to a midlatitude late-afternoon region of the planet. The orbiting bus is spin-stabilized, and its design and many of the probe subsystems are based on subsystem developments and technlogy from Pioneer Venus. The conceptual launch configuration is shown in figure 42.

The design of this mission requires consideration of many facets, including orbit selection, propulsion, probe entry conditions, communications, tracking, and configuration selection. For the specified entry sites, the probes are not visible from Earth, except for the polar probe, so that probe data must be transmitted to the orbiter and relayed later to Earth. The probe descent time is about 1 hr; for near real-time data transmission to the orbiter, the probe must be visible to the orbiter during the entire descent plus the time needed to recover landed science after impact. An alternative approach is to store data on the probes and to relay it to the orbiter at a high data rate during the probe final descent phase and for a short period on the surface.

After considering many of the above factors, the following conceptual mission design has been established for the recommended mission. About 10-20 days before encounter, the high-altitude probe is released from the orbiter/bus so that it will enter near the subsolar point and the bus is deflected to miss the planet. To attain the necessary entry conditions for the high-altitude probe, a type-I interplanetary trajectory was chosen. The high-altitude probe enters the atmosphere about 17° in longitude ahead of the subsolar point with a -18° path angle. The probe descends to an altitude of 82 km, where the drag and lift increase enough to decelerate it strongly and turn the trajectory upward. It then climbs to an altitude of about 170 km, exchanging kinetic for potential energy, and descends along a nearly symmetrical course to an altitude of about 80 km, where it continues to decelerate to subsonic conditions at the subsolar point (fig. 43).

This entry trajectory poses a difficult probe-to-bus communication problem because of the widely varying communication geometry. It may be possible to design a near real-time communication link between the probe and the bus with an appropriate antenna design and judicious application of propulsive impulse first to speed up the probe and then to slow down the bus to obtain the required probe-to-bus visibility time (~1 hr). A more conservative approach would be to install additional data-storage capability on the probe

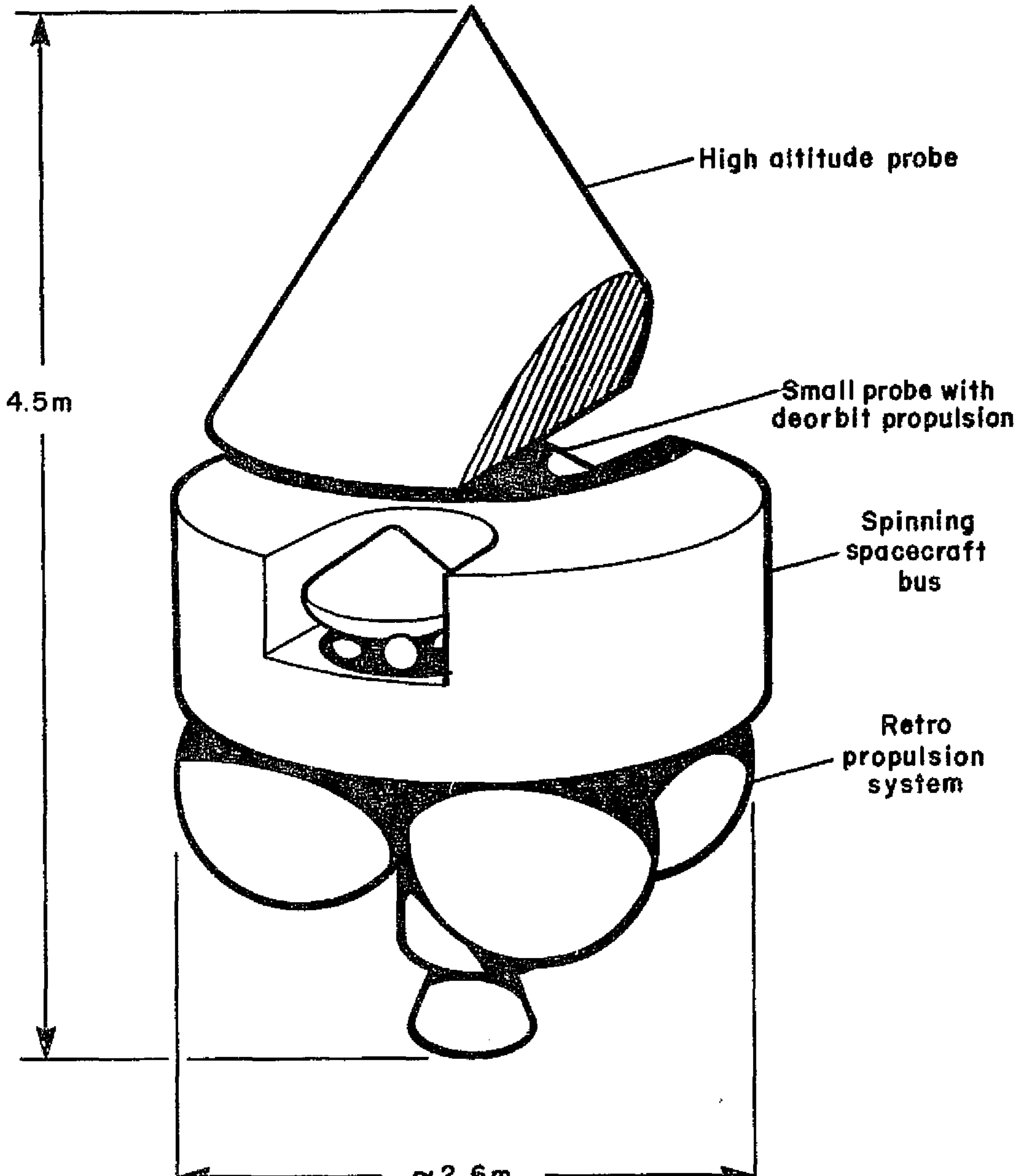


Figure 42.- Conceptual spacecraft launch configuration.

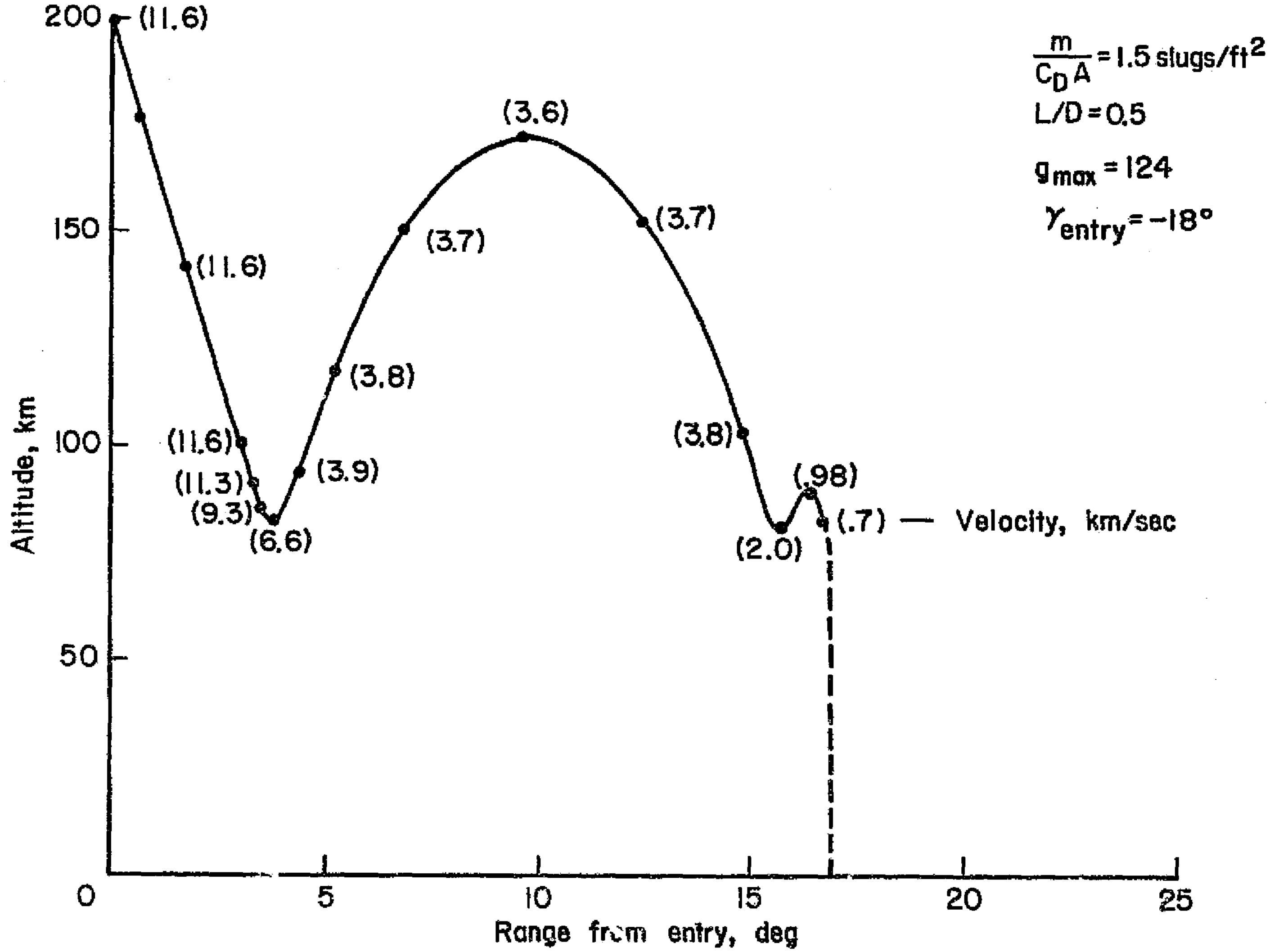


Figure 43.- High-altitude probe entry trajectory.

and to transmit the probe data to the bus at a high rate during the later phases of the probe descent and for a short time after impact. This latter approach appears feasible and was selected as the baseline for this study. It may be desirable to establish the feasibility of the former approach in later system tradeoff studies.

After the bus receives the data from the high-altitude probe, it rapidly approaches periapsis, where an orbit-insertion maneuver is performed. To minimize the orbit insertion, orbit maneuvering, and subsequent probe de-orbit propulsion requirements, a highly elliptical capture orbit was chosen with periapsis altitude = 500 km, eccentricity = 0.834, and a period of 24 hours. Furthermore, as a compromise orbit to satisfy simultaneously the communication requirements for all the probes, the capture orbit is inclined at 60° to the equator. After the completion of the orbit-insertion maneuver, the large retropropulsion system is jettisoned to minimize the effect of propellant residuals on center-of-gravity control.

At this time, the spacecraft consists of the basic orbiting bus and two small probes. Both small probes are mounted in the transverse plane of the bus center of gravity, so that the release of one probe at a time will yield a stable, spinning, orbiting bus configuration that does not wobble. Both small probes are de-orbited after the apoapsis of the capture orbit, and both probes require a crossrange velocity component to attain the desired entry sites (pole and late-afternoon midlatitude) from the 60° inclined orbit. In both cases, it would be expensive in terms of de-orbit velocity increment (ΔV) to obtain the required 1-hr probe-to-bus visibility time for real-time data transmission to the orbiting bus, so, as in the case of the high-altitude probe, the alternate approach of providing data storage on the probes for high data-rate retrieval during the later phases of probe descent was selected as baseline for this study. Again, it may be possible to devise a near real-time communications link through proper antenna design and application of the large ΔV to speed up the probes so they enter well ahead of the orbiting bus. These approaches should be compared in any subsequent system tradeoff studies.

To minimize the crossrange velocity increments necessary to de-orbit the small probes from the orbits selected in the study, the first small probe to be released is the polar probe. It will enter at a moderate entry angle. Finally, in a subsequent orbit, the remaining small probe is de-orbited for shallow entry in the afternoon quadrant of the planet. The orbiting bus is then available for conducting its own set of experiments until the completion of the mission.

7.5.1 Subsystem design - The basic system is composed of two small probes, a large lifting-body probe and a spacecraft bus. These system elements are discussed below. The de-orbit and retropropulsion systems are discussed in section 7.5.2.

7.5.1.1 Small probes: To maximize the use of existing hardware, the two small probes will use the same subsystems and are expected to retain as much similarity with their Pioneer Venus counterparts as possible. Some changes in instrument design and complement are required (discussed in section 7.4.2), along with increased data-storage capacity.

Aside from the modifications in science instruments, other factors that will perturb probe design are launch year, entry conditions, communications, and integration of de-orbit propulsion. To package additional instruments in the Pioneer Venus small probe, which is volume-limited, will require some scaling up of the probe. The advanced mission small probe is estimated to have a mass of about 110 kg (excluding de-orbit propulsion) and a diameter of 80 cm.

7.5.1.2 High-altitude probe: The design requirements for the high-altitude probe are to attain altitudes well above 100 km with velocities ≤ 4 km/sec. A preliminary system and entry trajectory study indicated that a lifting body with $L/D = 0.5$ and $M/C_DA = 1.5$ slugs/ft^2 would meet the stated design requirements and would lead to a realistic design and overall packaging arrangement. (The preliminary trajectory for the reference probe design is shown in figure 43.)

Both a 30° half-cone with a rounded nose (M-1 configuration) and a 30° truncated upper-surface cone (TLC - trim lifting cone) were examined as possible configurations for the lifting-body probe. A comparison of the two configurations indicated that, while the weights were about the same, the M-1 configuration was larger than the TLC configuration for the same ballistic coefficient; the TLC configuration seemed to offer some advantages in initial payload packaging, in communication by providing more surface for antennas, and in packaging with the spacecraft bus. For this reason, the trim lifting cone (TLC) probe shown in figure 44 was selected as the reference configuration for the study.

To retain as many of the subsystems from the Pioneer Venus large probe as possible, the spherical pressure vessel from the Pioneer Venus large probe (which contains the science instruments and electronics) was considered to be packaged in the TLC probe. There is about a 10-cm clearance between this spherical pressure vessel and the inside dimension of the high-altitude probe, so considerable flexibility exists in payload positioning to meet stability and trim attitude requirements. Some change in instrument complement and the addition of probe guidance and increased data-storage are required (26.1 kg as compared to 27.2 kg in the Pioneer Venus large probe).

The total mass of the high-altitude TLC probe is estimated to be 325 kg. This is based on the same heat shield and the same structural mass per unit area as the Pioneer Venus large probe and on a guidance package and internal structural allowance of 40 kg. The question of probe stability at low Mach numbers (to maintain the communications link) as well as integral versus staged entry of the instrumented capsule will require examination in subsequent studies.

7.5.1.3 Orbiter/bus: The various entry bodies will be delivered to Venus by the orbiter/bus spacecraft, which may also carry scientific instruments for examining the planetary environment. This orbiting bus will serve as a data relay for the probes. The bus is spin-stabilized and is expected to be similar to that used for the Pioneer Venus mission. The basic probe bus for the Pioneer Venus mission is a cylinder 254 cm in diameter by 122 cm high with a mass of about 230 kg.

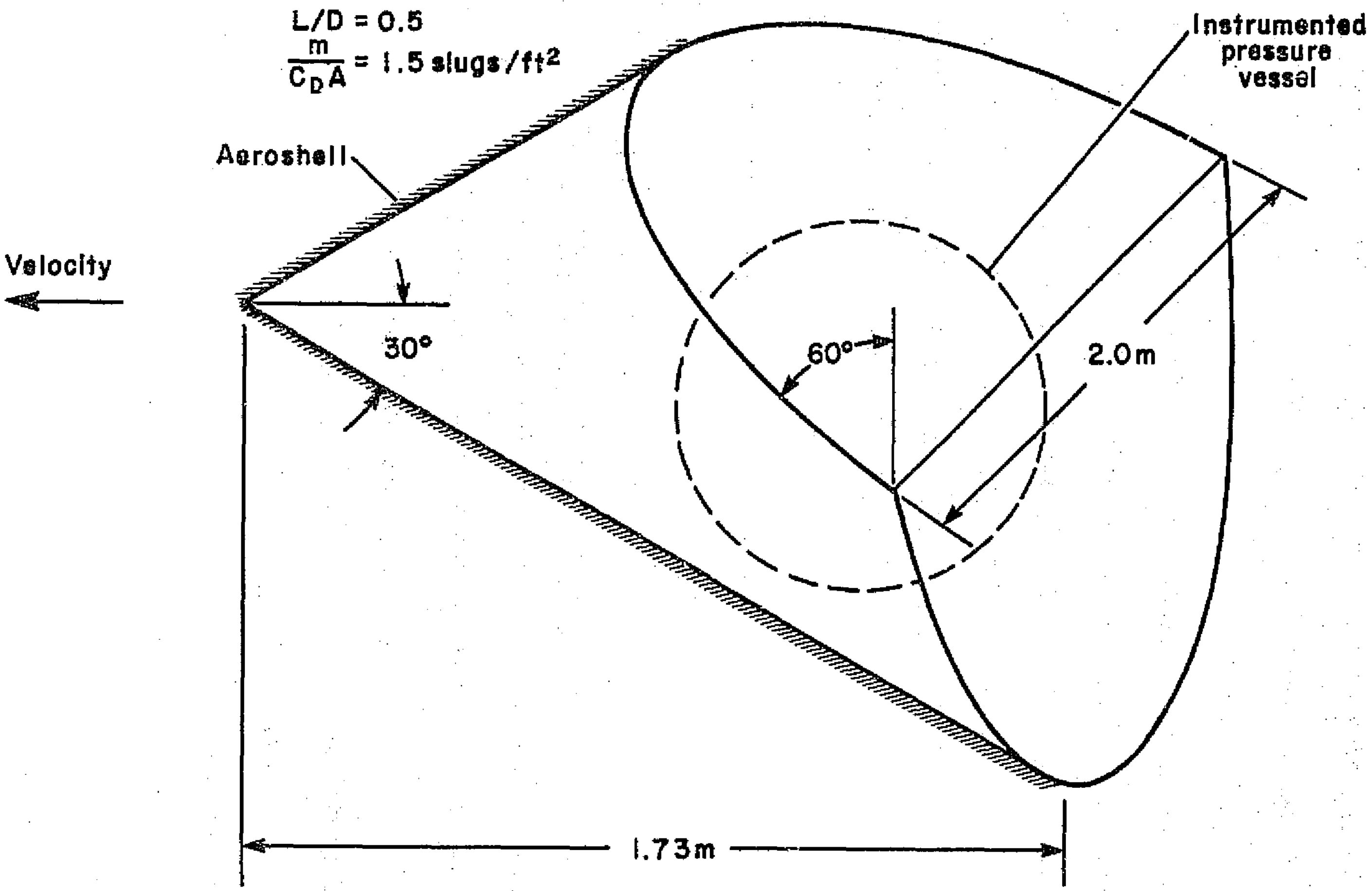


Figure 44.- High-altitude probe configuration.

7.5.2 Propulsion requirements - Propulsive maneuvers are required for midcourse correction, bus deflection, orbit insertion, orbit trim, and possible plane changes at Venus and for de-orbiting the small probes from the orbiting "bus." A highly elliptical orbit (periapsis altitude of 500 km, eccentricity of 0.834, 24-hr period) was chosen for this preliminary mission design.

7.5.2.1 Probe de-orbit propulsion system: To attain the required entry sites for the small probes, it is necessary to deploy them from an orbiting spacecraft. The probes are de-orbited near apoapsis and accelerated slightly to enter the atmosphere ahead of the bus to lengthen the probe-to-bus visibility time. The probe has a small de-orbit propulsion system attached to its afterbody. After the probe is de-orbited, the propulsion system is jettisoned.

The probe de-orbit and crossrange propulsion requirements can be provided by space-proven engines and components. It is estimated that a maximum ΔV capability of 250 m/sec should be sufficient for these maneuvers. The propulsion system selected for this application is a pressure-fed bipropellant system. For this system and de-orbit velocity, the de-orbit propulsion system weight increment would be about 20 percent of the basic probe mass.

7.5.2.2 Orbit-insertion propulsion system: The requirements for the orbit-insertion propulsion system are dependent on launch year, orbit, and orbital maneuvers. For favorable launch opportunities, the velocity increment required for the reference orbit is about 1.2 km/sec. These propulsive maneuver requirements are within the capability of a Viking-type (Earth-storable) propulsion system with modified tanks. The orbit-insertion propulsion system will add about 70 percent to the net in-orbit spacecraft mass. The additional velocity increments required in the mission for probe release, bus deflection, etc. will require additional propellant and will add about another 10 percent to the spacecraft mass.

7.5.3 Preliminary system characteristics - The baseline spacecraft is composed of an orbiting bus with its complement of probes and an orbit-insertion propulsion system. The conceptual system launch configuration (fig. 42) shows the small probes positioned in the plane of the bus center of gravity after deployment of the large high-altitude probe and jettison of the retro-propulsion system. The estimated weight breakdown of the basic spacecraft is shown in table XXVII. The total system launch mass requirement of about 1372 kg can be met by either a Titan or Shuttle derivative.

TABLE XXVII.- ESTIMATED SYSTEM MASSES

Large high-altitude probe		329 kg
Science instruments	26 kg	
Pressure vessel module (less science)	165 kg	
Internal structure and guidance	40 kg	
Aeroshell + structure	98 kg	
Small probes (each)		130 kg
Probe (includes 7.6 kg of science instruments)	110 kg	
De-orbit propulsion system	20 kg	
Orbiter/bus		250 kg
Retropropulsion system - 80 percent		408 kg
Contengency 10 percent		125 kg
Estimated launch mass		1372 kg

7.6 Entry Probe Summary

The opportunities for making further large strides in defining and understanding the atmosphere of Venus, past Pioneer Verus, lie in two areas: missions to explore regions of the planet and to measure regions of the upper atmosphere inaccessible in situ to the 1978 probes. Furthermore, investigation of fundamental properties of the clouds will be only begun with the 1978 experiments. Further definition of the deep-atmosphere circulation will be required because of the limitations on locations that can be probed in 1978. Information will be needed particularly for the vicinity of the subsolar point (the driving center of the circulation) and the poles. It is further expected that questions concerning the mixing of the atmosphere, which interact strongly with questions about key aspects of the atmospheric composition, will not be definitively resolved in 1978. In-situ investigation of the four-day circulation and its driving mechanism in the region above the clouds will also be incomplete. An understanding of this circulation and its mechanism is likely to be highly informative with respect to the total circulation.

Subsolar and polar entries are accessible to probes launched from an orbiter. Subsolar entry will require the use of relay communications through the orbiter, and wind measurements must be partially supported by onboard measurements (Doppler radar altimeter). The polar probe can be viewed from Earth down to the level of critical refraction (7-bar level). The third small probe, sent to investigate the afternoon atmosphere, will be out of sight of Earth during its entry and descent, and it requires relay communications.

The subsolar probe should also be dedicated to the in-situ exploration of the upper atmosphere, from 67 to 135 km, which has many questions not expected to be resolved by Pioneer Venus. This can be accomplished to the 170-km level by use of a lifting probe that climbs to this altitude using its kinetic energy after decelerating to a speed of 4 km/sec at altitudes below 90 km. The upper-atmospheric measurements are thus made at speeds ~3800 m/sec.

The suggested probe scientific payload has an aggregate weight of 41.3 kg, compared to 35.4 kg on the 1978 probes. The orbiter is capable of carrying scientific instruments in addition to the probes.

The three probes are launched from the orbiter bus one at a time and only the two small probes are carried into orbit, to save propulsion weight. The gross liftoff weight is about 1400 kg. Thus, the mission probably requires a space shuttle launch, although with careful attention to weight limitation it might be brought within the capability of an Atlas Centaur with a TE 364 upper stage.

8.0 BUOYANT VENUS STATIONS

Balloons are potentially an effective tool for studying the Venusian atmosphere. They offer several observational advantages: (1) direct coupling to the wind fields, (2) long lifetime, (3) in-situ measurements, and (4) the

capability of releasing dropsondes at interesting sites. The first two features would allow studies to be done on a global scale, as well as the investigation of temporal variations of atmospheric quantities.

The balloon system at float altitude consists of the balloon and gondola. The gondola contains the science instruments and possibly dropsondes. A typical conceptual layout of a Venus balloon system is shown in figure 45. The systems considered here use helium-filled balloons that maintain a constant displacement volume and hence a constant density altitude (see sections 8.4.1 and 8.4.3.3 for the effects on float altitude of updrafts and dropsondes). Current technology would limit balloon flotation altitudes to between about 55 and 70 km. Below about 55 km, ambient temperatures become excessive for the gondola electronics to survive and balloon lifetimes are short because the helium permeates rapidly through the balloon skin. For several reasons (discussed in sections 8.1 and 8.3), the attractiveness of balloon missions would be considerably enhanced by technology developments that would permit balloon operations down to altitudes of 30 to 40 km. Above about 70 km, the system design weight increases rapidly with increasing altitude and becomes prohibitively large in relation to payload weight.

Balloon design and lifetime are sensitive to ambient design conditions. Thus, the data that will be obtained from the Pioneer Venus mission would be of paramount importance to balloon system design (see section 8.4 for more details).

8.1 Science Rationale

The scientific limitations of Pioneer Venus and Earth-based measurements have been discussed in section 5.0 and further details appropriate to the material of this section was presented in section 7.0. Major atmospheric questions that may remain after Pioneer Venus and that could be effectively addressed by balloon missions are: global wind patterns, drive for the circulation (including the drive for the four-day upper-atmospheric rotation), atmospheric waves, properties of key regions of the atmosphere (subsolar and antisolar points, polar regions), cloud composition and distribution, and the effects of circulation and clouds on the structure of the atmosphere. In addition, appropriately instrumented dropsondes released from a balloon could investigate such surface properties as composition, density, and perhaps porosity. Each of the above subjects is considered in more detail below.

8.1.1 Global wind patterns - The importance of experimentally determining the Venus circulation pattern is emphasized when it is recalled that not one theoretical model of the Venusian atmosphere that existed before about 1969 ever gave a hint of the large mean zonal winds indicated by subsequent ground-based and spacecraft observations. Even at present, there is no adequate theoretical model describing the Venus circulation and what is currently known about it. Until sufficient data exist on global wind patterns, we cannot fully comprehend Venusian atmospheric processes.

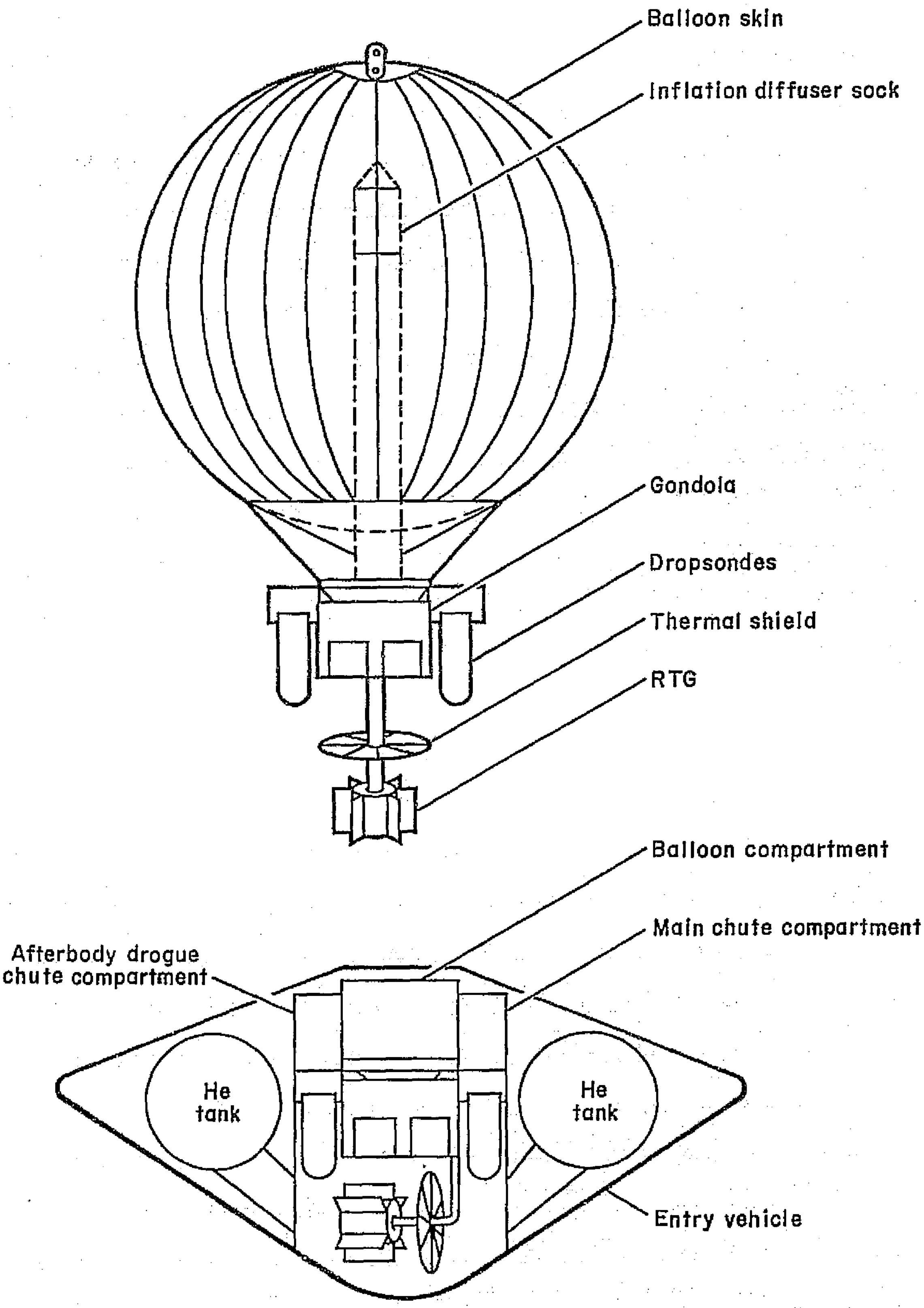


Figure 45.- Typical Venus balloon system.

Pioneer Venus cannot define global wind patterns because of a finite number of entry probe sites (4) constrained to be within 60° of the sub-Earth point. However, balloons drifting with the winds at different latitudes and altitudes could give a reasonable picture of the global circulation at the balloon float altitudes, and dropsondes released from the balloon could give wind information below the float altitudes. Exactly how many balloons would be required is not clear at the present time, but probably at least three would be desirable with each balloon carrying one or more dropsondes. Each balloon would carry a transponder to facilitate tracking, as well as an accelerometer and/or altimeter, for vertical wind determination. To obtain data concerning the winds on the side of the planet facing away from Earth would require either an orbiter or accelerometers, and the capability to store data until communications would be restored; in addition, for the latter, the assumption of negligible local crosspath winds might be necessary. The required accuracy of the horizontal wind measurements is a function of altitude, with an accuracy of 0.1 to 0.5 m/sec probably being sufficient at altitudes $\lesssim 20$ km, but an accuracy of $\gtrsim 10$ cm/sec probably being required in the lowest scale heights of the atmosphere. It would be desirable to detect vertical wind velocities as small as 0.1 cm/sec.

Variability in time of the large zonal winds with time scales >1 week is suggested by Earth-based observations. A confirmation of such variations, together with determination of their magnitudes, could give valuable insight into dynamical mechanisms. The capability of balloons for making measurements for periods of from one to several weeks would be valuable in studying this phenomenon.

8.1.2 Drive for the circulation - Although obtaining the global wind patterns is of primary importance, the patterns cannot give an understanding of dynamical processes unless the forcing functions to which they are the response are determined.

Thus, with the same resolution as the wind measurements, solar energy deposition, long-wave radiative heating, and pressure and temperature fields should be measured. A balloon could easily carry the necessary instrumentation, consisting of a net flux solar radiometer, net flux IR radiometer, and pressure and temperature sensors. Although such instruments are onboard Pioneer Venus, the much greater coverage, both in space and time, obtainable by balloons would allow the driving function for the circulation to be defined, to the extent that the response of the atmosphere to the solar energy input could be probably understood in terms of the observed wind patterns.

There is no doubt that one of the major goals of atmospheric missions to Venus should be to investigate the unexpected and unique situation whereby a planetary atmosphere apparently rotates between 25 and 60 times faster than the planet itself. Our knowledge of not only the Venusian atmosphere, but of atmospheric dynamics in general, will be incomplete until this phenomenon is understood. In this regard, complete zonal coverage over the planet at a minimum of one latitude would be of great value because the generating mechanism of the large zonal winds involves Reynolds stresses (zonal averages of the correlations of the components of the fluid velocity with each other) and the

variation of the temperature field with longitude. Of all the mission types considered in this report (i.e., orbiters, probes, landers), only a balloon mission has the potential capability of gathering enough information. This unique capability exists because the balloon instruments can make in-situ measurements of the appropriate quantities while traveling around the planet under the action of the mean zonal winds, but it should be noted that this capability is currently limited to the altitude range from 55 to 70 km.[3] It is known from Venera 7 and 8 data that the most rapid increase in the zonal winds occurs between 40 and 50 km altitude; hence reducing the current lower altitude limit to the latter range using advanced technology would be highly desirable.

8.1.3 Atmospheric waves - Atmospheric waves play an important role in the Earth's atmosphere, and there are strong indications they are important for the atmosphere of Venus. Gravity waves and Kelvin waves have been suggested as the generating mechanism of the four-day circulation. Further, atmospheric waves were apparent in the UV photographs taken by Mariner 10. For example, certain waves seen by Mariner 10 in the form of bow waves, apparently generated by flow about the subsolar region, are controversial phenomena of high interest which have no known Earth analog. The confirmation of these waves would be a meteorological discovery of possible significance to Earth as well as to Venus. Another type of wave was observed propagating toward the equator from the poles, with wave fronts parallel to constant latitude circles. The significance of these waves needs to be investigated further.

Of any of the possible mission types considered here, only balloons would have the potential capability of investigating wave phenomena in situ. Pressure cells in which the reference chamber is sealed at the local ambient pressure level would provide a sensitive device capable of detecting waves (personal communication, V. Suomi, 1975). However, to determine phase velocities and the direction of propagation and to distinguish different wave types, pressure cells would need to be carried on several balloons spaced around the planet.

8.1.4 Properties of key regions of the atmosphere - Pioneer Venus will not probe key regions of the planet, that is, the subsolar point and the poles. Mariner-10 photographs indicated that these regions are important to the circulation; small-scale convection and bow waves were observed near the subsolar point, and there appeared to be significant interaction between the mean zonal flow and the subsolar region, part of which is evidenced by the bow waves. In addition, significant latitude variations in the flow fields were observed, with indications of strong circumpolar vortices in the polar regions. Clearly, the subsolar point is the driving center of the circulation, while the polar vortices have been suggested by Murray et al. (ref. 69) to be a kinetic-energy sink. In any event, these regions have to be studied to increase knowledge of not only the circulation but also the energetics of the atmosphere.

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[3]Note that meridional velocities could be of sufficient magnitude to make complete zonal coverage at a given latitude impossible anywhere except near the equator, where meridional winds should be negligible. Pioneer Venus should indicate the magnitude of meridional wind velocities.

A balloon placed at the equator, where meridional winds should be negligible, would almost certainly be capable of reaching both the subsolar and antisolar regions under the action of the mean zonal winds. In addition, if meridional velocities are sufficiently large (and Pioneer Venus should tell us if they are), a balloon placed at a higher latitude could spiral to the pole during its lifetime. The ability to release dropsondes would enhance the scientific return of the balloon mission by yielding data on the vertical atmospheric structure of these interesting sites.

8.1.5 Cloud composition and distribution - Determination of the composition and distribution of cloud materials in the atmosphere is important for at least two reasons, in addition to interest in the clouds themselves. First, the horizontal and vertical distribution of solar heating, which drives the general circulation and, second, the thermal structure of the atmosphere, are almost certainly determined to a large degree by the cloud material. Thus, an understanding of these phenomena is probably intimately involved with an understanding of the clouds.

Further atmospheric missions should seek to quantify cloud properties with regard to composition and its variability with position, particle size and number density as functions of position, and optical and thermal properties. A balloon drifting with the winds and capable of releasing dropsondes could, with the proper instrumentation, measure the above quantities over a wide region of the planet. The instrumentation would consist partly of a direct cloud composition detector capable of measuring both condensibles and solid particulates, particle size spectrometer, and advanced nephelometers. Such instruments are discussed with regard to entry probes in section 7.4.1, but there is no reason to believe they could not be used readily by balloons. To obtain cloud optical and thermal characteristics, solar flux and infrared flux radiometers could be used. Measurements will be made by Pioneer Venus in each of the areas mentioned above. However, the much greater coverage afforded by balloons (together with dropsondes), coupled with improvements in instrumentation, should enable cloud characteristics to be defined to the level necessary to quantitatively understand cloud processes and their effects on circulation and atmospheric structure.

A less important but nevertheless very interesting set of observations could have to do with electrical phenomena in the clouds, for example, to detect precipitation. It is widely known (ref. 133) that when precipitation occurs within terrestrial clouds, charge separation mechanisms act to develop electric fields. In particular, Reiter (ref. 134) observed the development of altostratus clouds into nimbostratus (rain) clouds. He found that this development was coincident with the development of increasingly strong electric fields and that the magnitude of the electric field was predominantly determined by the rate of precipitation. Observations by Reynolds and Brook (ref. 124) and by Fitzgerald and Byers (ref. 135) also showed that electric fields differed from the fair-weather field only when radar returns showed the presence of strong precipitation. Observations of lightning activity in clouds (refs. 124 and 136-138) show that lightning occurs when both strong vertical updrafts and precipitation are occurring. There is no *a priori* reason to expect that such circumstances would not occur on Venus and therefore

the detection of both electric fields and lightning in the Venusian clouds could probably be used to locate areas of precipitation. The development of electric fields sufficiently strong to cause lightning does not appear to be dependent on the presence of water because such discharges have been observed when oil-spray systems have been operated (ref. 139). Instrumentation for the measurements might be similar to that being flown by the Pioneer Venus orbiter electric field experiment, which, however, is not likely to detect lightning discharges because of the shielding effect of the ionosphere.

8.1.6 Factors determining atmospheric structure - Pioneer Venus, using the temperature sounding infrared radiometer onboard the orbiter and the temperature sensors aboard the probes, should give a reasonable picture of the actual temperature variations in the atmosphere. The principal gaps in knowledge concerning atmospheric structure remaining after Pioneer Venus will probably be in our understanding of the processes that determine the thermal structure. One of the most important of these is the circulation, that is, through advection of temperature, compressive heating, etc. The circulation is almost certainly responsible for the small horizontal temperature contrasts of the upper atmosphere, and it is probably important in reducing the equator-pole thermal contrasts in the lowest scale heights of the atmosphere. Further, the large-scale circulation may be responsible for maintaining the adiabatic state of the lower atmosphere. Another major factor determining thermal structure is cloud composition and distribution; in fact, the clouds may be largely responsible for creating enough of a greenhouse effect to cause the large surface temperature of 740° K. Additionally, the latent heat release of cloud condensibles may be important.

Appropriately instrumented balloons would be ideally suited to study circulation effects on thermal structure at balloon float altitudes, and could also give information on energy deposition and the role played by the clouds as energy sources or sinks. The lower the limit on balloon float altitudes the better since, as mentioned above, circulation effects on thermal structure may be important at low as well as high altitudes. Possible instrumentation would be temperature and pressure sensors, solar and IR net flux radiometers, cloud composition detector, nepholometer, and a transponder to facilitate wind measurements.

8.1.7 Surface science - Although a balloon mission would be primarily oriented toward the neutral atmosphere, significant surface measurements could be done using appropriately instrumented dropsondes that could be released at interesting geologic sites. Such surface properties as composition, density, and porosity could be studied. The instrumentation that might be used is discussed in some detail in section 9.0 in connection with lander missions. Basically, it would probably consist of an x-ray spectrometer and/or x-ray fluorescence analyzer and accelerometers.

8.2 Candidate Instrument Packages

Suggested science instrumentation to be carried by a balloon and the questions addressed by the individual instruments were discussed in section 8.1;

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briefly, the instrumentation includes a transponder to facilitate balloon tracking; temperature and pressure sensors to characterize atmospheric structure and detect planetary waves; solar and infrared net flux radiometers to determine energy deposition, drive for the circulation, and cloud absorption and scattering properties; cloud properties sensors, including a direct cloud composition instrument and electric field and discharge detectors; a three-axis accelerometer to aid circulation measurements and studies of turbulence; and a gas chromatograph and/or mass spectrometer to study atmospheric composition. In multiple balloon missions, it would not be necessary for each balloon to carry all the above instruments, but rather each balloon would carry appropriate combinations of instruments so as to maximize the total science as a function of system weight.

The instruments fall easily into four groups or options given in table XXVIII. Option 1 represents the absolute minimum capability of a balloon. It would enable accurate tracking of the balloon to determine wind patterns, but nothing more. Option 2 would make measurements relevant to almost all the scientific questions discussed in section 8.1, except cloud composition and distribution. Option 3 is dedicated to cloud characterization measurements. Option 4 measures atmospheric composition.

TABLE XXVIII.- CANDIDATE INSTRUMENT PACKAGES

Science option	Instrument	Weight (kg)	Volume (cm^3)	Power (W)
1	Transponder	2.0	---	22.0
2	Altimeter	0.5	280	5.0
	Temperature sensor	.5	200	1.0
	Pressure sensor	.5	200	1.0
	Three-axis accelerometer	1.3	1200	2.9
	Solar flux radiometer	1.8	1700	4.0
	IR flux radiometer	2.5	1540	4.0
	Total	7.1		
3	Cloud composition detector	3.0	1600	5.0
	Nephelometer	.8	1130	1.8
	Electric field detector	.5	300	1.0
	Electric discharge detector	.5	300	5.0
	Total	4.8		
4	Mass spectrometer	10.0	9500	32.0
	Gas chromatograph	5.5	8600	14.0
	Total	15.5		

Although the scientific instrumentation discussed above has, for the most part, been suggested by previous studies of balloon missions, the measurements that would be done are fundamental to our understanding of the Venusian atmosphere. Much of the instrumentation developed under the Pioneer Venus program and other Venus exploration missions could be readily adapted to a balloon mission with minor modifications, such as scale changes for balloons floating above a 50-km altitude. The major gaps in instrumentation capability are the

lack of a direct cloud-composition detector and instrument electronics capable of working for extended periods at high temperatures. Further research should therefore be devoted to the development of an instrument to measure cloud composition (with emphasis on solid particulate analysis) and the development of high-temperature electronics.

Dropsondes would be valuable additions to a balloon mission because of their capability of exploring the atmosphere below the balloon flotation altitude. Furthermore, dropsondes instrumented with surface science packages should be included in any balloon mission. Possible instrumentation, not all of which would be carried by each dropsonde, would include a transponder, pressure and temperature sensors, cloud composition detector, nephelometer, solar and infrared net flux radiometers, and instruments to investigate surface properties such as composition, porosity, and density. Table XXIX illustrates possible dropsonde instrument packages.

TABLE XXIX.- DROPSONDE SCIENTIFIC INSTRUMENTS

Dropsonde	Instrument	Total dropsonde weight (kg)
1	Transponder Temperature sensor Pressure sensor Cloud-composition detector	11
2	Transponder Temperature sensor Pressure sensor Solar flux radiometer Infrared flux radiometer	12
3	Transponder γ-ray spectrometer x-ray fluorescence analyzer Accelerometer	12

8.3 Candidate Mission Options

Selection of balloon mission strategy (i.e., single vs. multiple balloons, latitude vs. altitude coverage, etc.) will depend on the results of Pioneer Venus and the Soviet exploration program, as well as existing technology at the time of mission inception. In spite of this uncertainty, several general comments concerning mission configuration can be made. First, there are several scientific reasons (see section 8.1) for preferring multiple balloons to a single balloon. Secondly, dropsondes should be an integral part of any balloon mission, both from an atmospheric science and surface science point of view. Finally, the use of an orbiter in conjunction with one or more balloons would have several scientific and data-handling advantages and should therefore be considered if a balloon mission is initiated.

Table XXX lists three sample missions considered in the present study, which, by necessity, were configured under current technological constraints. It should be understood that these missions are examples that provide a basis

for engineering analysis; the final selection of float altitude, entry latitude, etc., depends, as mentioned above, on several factors.

TABLE XXX.- CANDIDATE MISSION OPTIONS

Mission option	Total number of BVS	Entry latitude	Float altitude	Science option	Number of dropsondes		
					Type 1	2	3
A	3	0	65	1,2,3,4	1	1	1
		45	65	1,2,3	0	1	0
		80	65	1,2,3	0	1	0
B	1	0	65	1,2,3,4	1	1	1
C	3	0	65	1	0	0	0
		45	65	1	0	0	0
		80	65	1	0	0	0

Mission option A would give a reasonable picture of large-scale Venusian meteorology, including cloud composition and distribution; it examines driving mechanism of four-day circulation in two dimensions at constant altitude.

Mission option B would give an idea of equatorial meteorology of atmosphere, including cloud composition and distribution; it examines driving mechanism, four-day circulation in one dimension, at constant altitude along the equator.

Mission option C obtains global wind patterns only at the 65-km altitude level.

In the multiple balloon missions given in table XXX, it was deemed more desirable to place the balloons at different latitudes than at different altitudes at the same latitude. There are several reasons for this choice. First, with current technology, the altitude range of balloons is restricted to between ~55 and 70 km, a region only 15-km thick. Although this region may contain the tropopause, dropsondes could give much better altitude coverage. Secondly, Mariner-10 UV photographs indicated important variations of the circulation with latitude, and it would be very desirable, not only from the standpoint of the circulation but also from the standpoint of the thermal structure of the atmosphere, to investigate these latitude variations. (Longitude coverage is, of course, also important, but a balloon should have this capability due to the mean zonal winds.) It would be highly desirable, however, to always place at least one balloon in equatorial regions so that the subsolar and antisolar regions are studied.

It has been assumed that meridional velocities are small enough that a balloon remains approximately on a constant latitude circle as it travels around the planet once under the action of the mean zonal winds. If meridional velocities are large enough that a balloon rapidly spirals toward the polar regions, the initial latitude placement of some of the balloons would probably be different than that listed in the table. As mentioned before, Pioneer Venus should give the necessary information.

A minimum acceptable lifetime for a balloon has been taken as 8 days; thus a balloon would make at least one complete revolution about Venus and perhaps two during its lifetime, allowing for uncertainty in zonal wind speeds. Note that a balloon itself could act as a vertical probe as it descends at the end of its flotation lifetime. If the flotation time remaining can be monitored, it might be possible to command the balloon to descend where desired (e.g., the subsolar point).

With advanced technology, the principal modification to missions such as those in table XXX would be reduction of the lower altitude limit from ~55 to 30-40 km. This would be desirable for three reasons: First, the region between 40-50 km appears to be the location of the most rapid increase of the mean zonal winds; second, 35 km appears to be the approximate lower boundary of the clouds; and, finally, remote sensing of the atmosphere below the top of the clouds is very difficult, so that in-situ measurements are especially valuable for obtaining information in these lower regions. Assuming that the lower altitude could be reduced to ~30 km, the strategy of balloon placement as well as the number of balloons desired would require further consideration. It appears that more than three balloons would be advantageous if good altitude and latitude coverage were to be obtained.

8.4 System Engineering Analyses and Design

8.4.1 Description and general engineering considerations - Venus balloon missions have been analyzed in a number of preliminary design studies (refs. 140-147). These studies examined mission feasibility, established conceptual designs, and examined many of the system tradeoffs for balloons that float in the altitude ranges between about 50 and 70 km. Studies have not been performed for balloons that float below 50 km altitude. The desirability for operation at lower altitudes (discussed earlier in the science rationale) poses severe technological problems because of the increased ambient temperatures (discussed in more detail later). Some of the general engineering considerations associated with a typical Venus balloon mission and a brief mission description will follow; many of these considerations are general and independent of the float altitudes.

The balloon system will arrive at Venus packaged in an entry aeroshell. This entry aeroshell is carried by a spacecraft bus during the launch and interplanetary cruise portion of the mission. The overall balloon system (fig. 46) consists of a balloon, a gondola, a gas storage and fill system, a parachute, and an entry aeroshell. The gondola contains the science instruments and dropsondes. Packaging all this equipment inside the aeroshell will be a significant problem; however, viable packaging arrangements have been developed in some of the preliminary design studies cited above. Studies have indicated that multiple small balloons can be packaged in a single aeroshell for deployment at a given entry location. For multiple balloons and multiple entry locations, separate aeroshells are required for each entry location.

Upon arrival at Venus in the entry vehicle, the balloon system is deployed as shown in figure 46. After the aeroshell has entered the atmosphere and has

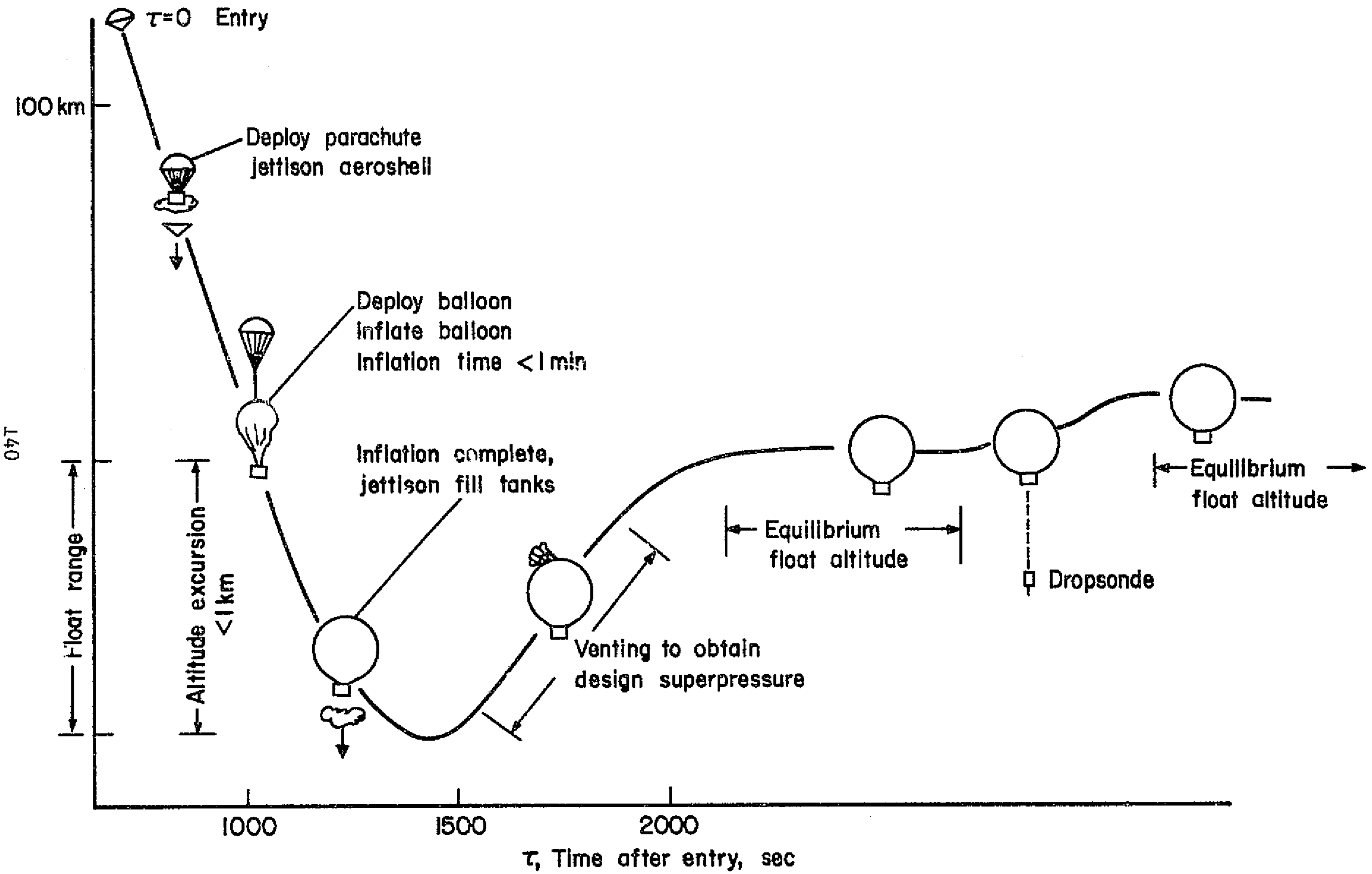

Figure 46.- Balloon deployment sequence.

slowed to subsonic velocity, a parachute is deployed and the aeroshell is jettisoned. The parachute slows the balloon system to about 10 m/sec. Near the desired float altitude, a barometric switch signals balloon deployment and inflation. After completion of inflation, which takes less than 1 min, the parachute and gas fill tanks are jettisoned. The balloon slowly recovers and rises to its design altitude.

The balloon systems that have been given the most attention use a helium-filled superpressure balloon, which maintains a constant displacement volume and hence a constant density altitude. In the superpressure balloon, excess gas is initially stored in the balloon to provide the desired balloon longevity. Since the balloon is a pressure vessel, this excess gas coupled with temperature effects cause the pressure inside the balloon to be greater than the ambient pressure. This overpressure difference is called the superpressure.

These superpressure balloons float with the winds until the internal pressure equals the ambient pressure (zero superpressure) at which the balloon volume starts to shrink. The most likely location for balloon failure is at the evening terminator when the balloon cools down and the internal pressure decreases; if the internal pressure drops excessively and the balloon shrinks, the balloon will sink.

The balloon design and lifetime are sensitive to ambient design conditions. The data that will be obtained from the Pioneer Venus missions are critical to the design of the balloon system. Examples of the information for which better estimates are expected from Pioneer Venus are the circulation patterns, updrafts, solar flux at design altitude, and the concentrations of the acids in the clouds.

Sustained updrafts create problems for superpressure balloons by driving them upward into regions of lower ambient pressure, thereby increasing the effective superpressure. When this excess superpressure exceeds the structural limit, gas must be vented to maintain the acceptable pressure difference. In the limit, sufficient gas could be vented to cause the balloon to sink once the updraft ceases. The current design estimate for the updrafts is 5 m/sec; updrafts greater than about 8 m/sec create serious balloon design problems and premature failure of the balloon after updrafts subside. Because of the problems created by the updrafts, other balloon types should be examined in subsequent studies.

The balloon design is sensitive to the thermal heat balance (incident solar flux) and to possible reactions with ambient constituents (e.g., H_2SO_4). The effects of the ambient constituents on the strength, permeability, and optical properties of the balloon are important to the balloon system design. The optical properties of the skin affect the balloon temperature and thus the design superpressure and permeability. These latter two items have a significant impact on balloon system weight and lifetime. Current superpressure balloon skin designs are based on a bilaminate of dacron over mylar, which is known to react with concentrated solutions of H_2SO_4. Development of other materials such as a trilaminate with an outer acid-resistant layer may be necessary, depending on the findings of Pioneer Venus.

Current technology limits allowable balloon flotation altitudes to a range between about 50-55 and 70 km for superpressure balloons. Below about 50 km, ambient temperatures become excessive for the gondola electronics to survive, and balloon lifetimes are short below altitudes of about 55 km because the helium permeates rapidly through the balloon skin. Balloon lifetime tends to increase with increasing altitude. Above about 70 km, the system weight increases rapidly with increasing altitude and becomes prohibitively large; for instance, the system weight approximately doubles when the design altitude is increased from 70 to 75 km.

To achieve float altitudes lower than about 50 km will require advances in balloon skin and electronics technology to operate at the high temperatures that exist at these lower altitudes. At an altitude (H) of 50 km, the ambient temperature (T) is $\geq 354°$ K (175° F); at $H = 40$ km, $T \cong 433°$ K (320° F); and at $H = 30$ km, $T \cong 524°$ K (485° F). Studies are required to examine the feasibility of balloon systems at lower altitudes, to perform system tradeoffs, and to assess the technology development and costs. The increased cost of these balloon systems must be justified on the basis of the increased science return. Alternative techniques for obtaining data at the lower altitudes also must be examined as part of any future study efforts.

8.4.2 Characteristics of candidate missions - The sample mission options developed for this study are described in section 8.3. These options consist of a selection of payloads and entry sites. Preliminary system characteristics were established for each candidate mission and payload option. The estimated float mass, balloon size, expected lifetime, helium storage-system mass, aeroshell mass, and total entry weight of each option are shown in table XXXI. Balloon diameters ranged from about 7.6 to 12.4 m. All balloons (since design altitudes were greater than 50 km) exceeded the desired minimum design life of 8 days and are capable of operating for an indefinite period. Communication, data-handling, power, and structural subsystem weights used in developing these designs were obtained by perturbing the detailed weight breakdowns for similar systems given in the referenced preliminary design studies. This was accomplished by estimating the effect of differences in design requirements between this study and the references. Table XXXII lists the estimates of the gondola subsystem weights used to develope the designs for the candidate mission options.

The launch requirements for each candidate mission option are also summarized in table XXXI. The combined entry mass was obtained by summing the entry masses for the individual entry systems within each mission option. The launch vehicle injected mass requirements were found by adding an estimated bus weight of 350 kg to the combined entry mass for each mission option (plus a 10 percent contingency) and comparing this to the launch vehicle capabilities shown in appendix B for $C_3 = 10$ km^2/sec^2. The results indicated that multiple simple balloon systems containing a transponder could be launched with a single-stage Titan launch vehicle and that the most sophisticated options would require a Shuttle/IUS or Titan III E/Centaur. In the options requiring multiple entry probes, the probes are mounted on a common bus and released as required to achieve the desired entry locations.

TABLE XXXI.- BALLOON SYSTEM DESIGN CHARACTERISTICS FOR CANDIDATE MISSION OPTIONS

Mission option	Balloon number	Float altitude, km	Entry latitude, deg	Gondola weight, kg[a]	Balloon diameter, m	Est. float time, days	Float weight, kg	Inflation system weight, kg	Entry weight, kg	Launch weight, kg[b]	Minimum launch vehicle required
A	1	65	0	126	12.4	>100	248	370	1025		Titan/ Centaur (or equivalent)
	2	65	45	80.9	10.9	>100	167	252	739	3138	
	3	65	80	80.9	10.9	>100	167	252	739		
B	4	65	0	126	12.4	>100	248	370	1025	1512	Titan IIIC (or equivalent)
C	5	65	0	21	7.6	90	57	89	351		Titan IIIC (or equivalent)
	6	65	45	21	7.6	82	57	89	351	1543	
	7	65	80	21	7.6	79	57	89	351		

[a]Includes dropsondes.
[b]Includes 10-percent contingency.

TABLE XXXII.- ESTIMATED GONDOLA WEIGHTS (kg) FOR CANDIDATE MISSION OPTIONS

Mission option	A			B	C		
Balloon number	1	2	3	4	5	6	7
Science	29.4	13.9	13.9	29.4	2	2	2
Communications	4.5	4.5	4.5	4.5	2	2	2
Data handling	16	16	16	16	4	4	4
Power	11.1	9.5	9.5	11.1	5	5	5
Structure	30	25	25	30	8	8	8
Subtotal	91.0	68.9	68.9	91.0	21	21	21
Dropsondes	35	12	12	35	0	0	0
Total	126	80.9	80.9	126	21	21	21

8.4.3 Subsystem design - Some of the key subsystem requirements and tradeoffs are described below.

8.4.3.1 Telecommunications: There are two means by which balloon science data may be returned to Earth: a relay link via an orbiter to Earth and a direct balloon-to-Earth link. The direct link offers the advantage of reduced system complexity and expense in that an orbiting vehicle is not required, but it offers the disadvantage of reduced overall telemetry capability. The consequences of using a direct link are that data taken on the backside of Venus must be stored, the balloon can be tracked only on the Earth side of Venus, dropsondes must be released on the Earth side of Venus for tracking by the deep space network (DSN) or they must be tracked by the balloon and there is a risk of significant data loss caused by balloon failure before emergence from the backside. Both methods are feasible and must be compared in more detailed tradeoff studies. Each option is summarized below:

(1) Relay link - A Venus balloon relay link has been examined in detail in several mission studies. The link described in the report by the Martin-Marietta Corporation (ref. 146) is typical. In that study, the orbiter is placed in an elliptical orbit of 1000 km by 30,000 km altitude. To provide good coverage of one hemisphere, periapsis is placed at the equator and the orbit is inclined 40°. Balloon data are stored in a 0.5-Mbit memory, which typically is emptied once each orbit period upon command. These data are then relayed via the orbiter to Earth. The orbiter carries 1 Mbit of storage to record orbital science.

For a relay link, the critical channel is that from the balloon to the orbiter, and that channel is most nearly marginal near apoapsis. At apoapsis, the range to the balloons can be as large as 35,000 km (for the above orbits), and the guaranteed contact time is only 65 min. This requires at least a telemetry rate of 128 bits/sec to unload the 0.5-Mbit memory, which can be achieved with a 5-W transmitter and a wide-beam (120°) antenna on the balloon gondola.

(2) Direct link - A direct balloon-Earth link is similar to that which would be required for the orbiter-to-Earth portion of the relay link. This type of link has been extensively analyzed and compared with a relay link (see ref. 143). For the system under consideration, the direct link cannot compete with a relay link in terms of channel capacity or total data return.

For the direct link, the balloon must remain in contact with the Earth, which requires communications over a balloon travel arc up to at least 60° from the sub-Earth point. This requires a wide-beam antenna. Since the balloon floats in the upper atmosphere, the degree of ray bending and turbulence introduced by the Venus atmosphere should be minimal, even when the balloon approaches the planetary limb. The Deep Space Network (DSN) is capable of receiving both S-band and X-band signals; however, the lower frequency is preferred to minimize noise and attenuation. The 64-m DSN subnet is essential to this option to provide adequate sensitivity.

Based on a four-day wind rotation pattern, the duration of balloon motion across the Venusian disk visible from Earth for communications purposes is

approximately 32 hr. During this period, the data link must unload the data accumulated during 64 hr of noncontact (stored in a 1-Mbit memory) as well as transmit the on-going measurements.

8.4.3.2 Tracking: Balloon tracking can be accomplished by various techniques, either directly from Earth or in conjunction with an orbiting spacecraft. These alternatives must be evaluated and compared in more detailed tradeoff studies that consider cost, science return, data handling, hardware, and other mission design requirements in establishing the optimum telecommunication and tracking modes. The major candidate techniques that provide accuracies sufficient to determine circulation patterns are described below.

(1) Combined orbiter/dual-station Earth tracking - This technique, which uses two widely separated Earth stations to measure the range and range rate of the orbiter and balloon simultaneously, is called the Doubly-Differenced Long Baseline Interferometry (DLBI) method. In this manner, Earth-Venus transmission errors are differenced and cancelled out to produce position and rate accuracies of <1 km and <1 m/sec, respectively. This method is limited to balloon observations on the Earth side of Venus; on the backside, tracking must be from the orbiter only.

(2) Earth-based tracking (modified dual-station) - This technique, called Delta Doubly-Differenced Long Baseline Interferometry (∇DLBI), uses two widely separated Earth stations to determine the relative positions between a fixed, known radio source (quasar) and the balloon. These positions are differenced to yield a relative position error of less than 100 m. When the ephemeris uncertainty of Venus is factored in, this leads to a position uncertainty for the balloon at Venus of approximately 1 km. An orbiting transponder at Venus could be used to reduce position errors to less than 100 m. This technique is limited to tracking on the Earth side of Venus.

8.4.3.3 Dropsondes and surface penetrators: Both dropsondes and surface penetrators have been proposed for Venus balloons in previous studies. Dropsondes appear attractive and can be used to obtain such atmospheric measurements as vertical wind profiles and cloud composition below the flotation altitudes. A suitably instrumented and designed dropsonde would have the capability of making significant surface measurements. Subsurface penetrators deployed from balloons, however, do not appear attractive because of limited penetration depth and short lifetimes. The diameter, length, and mass of the penetrators becomes prohibitively large to survive the thermal environment during descent and for reasonable times on the surface. Penetrators are described in more detail in section 9.0.

When dropsondes are released, the balloon equilibrium float altitude increases slightly due to the mass change. Dropsondes tend to increase balloon longevity since they serve as ballast. The dropsonde release location can be controlled by command, but such a command system should have an automatic override so that, if the balloon starts to sink, a dropsonde is released to increase lift by decreasing the total floated mass.

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8.4.3.4 Power system: The estimated power requirements for the various mission options varies substantially, depending on the sophistication of the payload. The estimated power requirements range from 2 W for a simple transponder to 20 W for a large balloon payload. Tradeoff studies (ref. 146) that considered primary batteries, solar cells, and RTG's have indicated that, for lifetimes greater than a few days, an RTG plus NiCd battery system is the most weight-effective system. The RTG system presents some problems related to packaging, thermal control, and possible interactions with the balloon skin and science instruments that will have to be examined in more detailed system studies.

8.4.4 Technology requirements - Much of the scientific instrumentation developed under the Pioneer Venus program and other Venus exploration missions can be readily adapted to a balloon mission with minor modifications, such as scale changes for the altitude ranges above 50 km. The one major gap in instrumentation capability is the lack of a direct cloud-composition detector. Further research into the development of an instrument to measure cloud composition (with emphasis on solid particulate analysis) is required along with studies that address the impact of low-altitude operation on the instrumentation.

The major technological developments associated with the balloon system itself are expected to be concentrated in the areas unique for this mission. The key projected technology problems that are foreseen are associated with gondola power supply, balloon deployment, packaging, and materials development. A reliable packaging, deployment, and inflation technique is critical to success of the mission. In addition, the system must survive in the environment of Venus for an extended period. Balloon skin materials will be required that can resist UV damage, limit permeation at elevated temperatures, resist sulfuric acid degradation to both strength and optical properties, and resist leakage due to packaging and deployment stresses. The identification of the necessary technology developments, to a large extent, hinge on the findings of Pioneer Venus. Studies are required to address the question of low-altitude balloon feasibility and to identify the technology development efforts required for such balloon systems.

8.5 Summary

Balloons are potentially an effective means of investigating several key atmospheric scientific questions that will remain after Pioneer Venus. Among these are global wind patterns, drive for the circulation, atmospheric waves, properties of key regions of the atmosphere (subsolar and antisolar points, polar regions), cloud composition and distribution, and effects of circulation and clouds on the structure of the atmosphere. In several areas, balloons represent the only means of obtaining enough information so that definitive answers appear at least possible.

Balloons are also potentially capable of contributing significantly to our knowledge of the surface of Venus through the use of dropsondes. Appropriately instrumented and designed dropsondes, released from a balloon, could be capable of investigating surface composition and soil properties over widely

separated regions, as the balloon floats over different geographical areas. In fact, if after a VOIR mission it was desirable to distribute many simple geochemical experiments over the Venus surface, balloons would represent a logical combination of surface and atmospheric missions into a very efficient single mission.

Balloon mission design will depend on the results from Pioneer Venus and the Soviet exploration program, as well as existing technology at the time of mission inception. Nevertheless, it is possible to identify certain general characteristics of an optimal balloon mission. Multiple balloons appear more attractive scientifically than any single balloon, although the exact strategy of placement would have to await further data gathered by preceding missions. Dropsondes should be an integral part of any balloon mission, both from an atmospheric science and surface science point of view. As discussed above, a balloon mission incorporating dropsondes equipped with appropriate surface science packages would be very attractive. Finally, a combined balloon-orbiter mission would offer several scientific and communications advantages and should be considered if a balloon mission is initiated.

Principal technology requirements were identified in section 8.4.4. Two of these directly affect the scientific return from a balloon. One is the development of a direct cloud composition detector capable of both condensible and solid particulate analysis, which should have high priority. Such an instrument would unambiguously answer a number of questions concerning cloud physics and could be used equally well by an entry probe mission if that type of mission were selected as the next atmospheric mission after Pioneer Venus rather than balloons.

The second technology requirement is to reduce the lower limit on float altitude from ~55 to ~30 km. This would significantly enhance the scientific return for three reasons: (1) The most rapid increase of the zonal winds evidently occurs between 40 and 50 km altitude, (2) The lower boundary of the clouds is located at about 35 km, and (3) In-situ measurements are especially valuable in these regions because of the difficulty of remote sensing below the visible cloud tops.

The sample mission options discussed in section 8.3 were configured assuming current technology, since it was impossible to assess quantitatively the impact of technological advances. Therefore, the sample missions should be viewed as examples that provide a basis for engineering analysis. Some general conclusions are possible. Multiple balloons placed at different latitudes would have much less scientific payload for the same launch weight as a single balloon carrying a considerably more sophisticated payload. This is due to the requirement of separate entry shields for balloons placed at widely separated locations horizontally. There are, however, considerable scientific reasons for wanting balloons horizontally distributed about the planet. Further, in the time frame when a balloon mission would be launched, the shuttle plus an upper stage should have more than enough launch capability for a comprehensive multiple balloon mission.

9.0 LANDERS

9.1 Lander Science Rationale

There is little direct knowledge of the composition, structure, and history of the solid components of Venus. To date, one measurement of surface density and a single γ-ray spectrum have been obtained by direct measurement (ref. 148). Radar maps of surface morphology have been obtained (refs. 84-86 and others), radar tracking has provided precise determinations of the radius (6052 ±2 km), and tracking of spacecraft flybys has led to a mass value of 1/408524th that of the Sun, but most other measurements have been of atmospheric properties. Knowledge of atmospheric composition and processes will have increased significantly by the 1980's as will information with regard to gross planetary morphology. Additionally, some information regarding surface composition may come from the active Venera program and from the proposed VOIR mission. Knowledge of surface and subsurface properties will remain meager and poorly defined, however, until an intelligently sited set of in-situ measurements is obtained. It is instructive at this time to review briefly the knowledge that exists and the inferences that can be made about the composition, structure, and evolution of Venus to identify the most urgent needs for information.

9.1.1 Planetary evolution - The similarity of mass and density of Venus and Earth and their location in the solar system suggest that these planets have broadly similar compositions. There is much argument as to how similar the compositions are and, even if their accretionary histories were similar, how they may have followed divergent evolutionary paths, particularly with regard to their volatile contents.

Lewis (refs. 121, 149, and 150) has proposed that Venus could have formed from primitive material devoid of water and other volatiles, particularly sulfur, and that quantities of such volatiles present now are compatible with amounts contributed by infalling cometary debris. Arrhenius (ref. 151), on the other hand, points out that both Venus and the Earth may have accreted heterogeneously, with the present zonal compositional distribution being determined by the evolution of the solar nebula. According to this model, water and other volatiles would have accreted on both planets in similar amounts, primarily in the later accretional states, but whereas it is possible to condense water and keep the surface temperature low on Earth, the blackbody temperature on Venus is sufficiently high to keep the water and other volatiles in the atmosphere, resulting in a runaway greenhouse effect. Although not specified, Arrhenius must assume that the atmospheric water was lost later, presumably by photodissociation, escape of the hydrogen and removal of O_2 by oxidation of surface materials. Fricker and Reynolds (ref. 152) have pointed out, however, that the amount of decomposed water that could be removed by the oxidation of surface regions of Earth is estimated to be less than 40 atm, far less than would be present in Venus' primitive atmosphere according to Arrhenius, and that the existence of a larger oxygen sink on Venus is unlikely. They have proposed a somewhat different model in which Venus did not have a massive primitive atmosphere, but, instead, most of the present atmospheric

constituents would have been contained inside an undifferentiated planet. Radioactive heating (and possibly tidal-friction heating) would raise internal temperatures, initiate fractionation, and result in the formation of a metallic core, the concentration of low melting constituents in outer layers and igneous activity with consequent escape of volatiles. Because of the black-body temperature at Venus, the accumulating atmosphere and its infrared absorbing constituents would initiate a runaway greenhouse (ref. 153) that would eventually increase the rate of magmatic activity and outgassing by modifying the temperature structure to a depth of several tens of kilometers. Accordingly, a massive atmosphere of secondary origin began to accumulate early with a feed-back control on the products of outgassing. Fricker and Reynolds (ref. 152) point out that the solubility of water in silicate melts increases strikingly with increasing pressure and speculate that, in contrast to Earth, more water would be retained in surface melts and in solid silicate materials on Venus because of the high vapor pressure at the surface. They suggest that only a small fraction of the available water would escape from the interior during the period of extensive melting, perhaps a few tens of atmospheres (less than 10 percent of the water at the Earth's surface).

None of the above hypotheses can be tested currently. It is evident, however, that the distribution of mass within Venus is zonal. The displacement of the center of mass from the center of figure and the granitic composition of surface rocks in at least one locality both suggest extensive differentiation and thus a thermal history not unlike that of the Earth. The lack of a strong magnetic field ($<4\gamma$ at the surface in the equatorial zone as inferred by Venera 4; ref. 26) is not contradictory to this finding; it could be due to the slow planetary rotation rate or perhaps to a smaller fluid outer core than is the case for Earth.

Clearly, if Venus is differentiated extensively, a complex thermal and igneous history is indicated. It is just as clear, however, that there is insufficient evidence to explore what that history may involve. Almost every measurement of surface property or observation of planetary morphology that might be made in the future could contribute evidence that would increase our understanding of Venus' evolution. Perhaps the most important contributions that could be obtained in the next few decades would derive from high-resolution radar mapping of the surface and from x-ray fluorescence and γ-ray spectrometric analyses of the elemental composition and natural radioactivity of classes of morphological units that are recognized on radar maps.

9.1.2 Surface relief and processes - Earth-based radar studies of Venus (refs. 84-86 and others) have demonstrated that the surface is cratered with craters (and basins) having observable diameters ranging from 35 km to over 1000 km. Furthermore, regional differences in elevation of the order of 6 km exist. Locally, relief has been identified as being related to specific land forms. A broad, asymmetric northrending ridge system some 6000 km long by 300 km wide with a height of about 3 km was described by Campbell et al. (ref. 84) and a 300-km-long linear feature with a width below the resolution limit (~15 km) has been observed by Rumsey et al. (ref. 86). The latter also described the relief of a 169-km-diameter crater, the most notable feature in a region some 1500 km in diameter where the total relief is of the order of

1 km. Total relief of the crater is only about 500 m, with the crater floor having about the same elevation as the surrounding terrain. Whether the limited relief of the crater is due to isostatic, erosional, or volcanic filling processes is uncertain. All processes may be active. Rumsey et al. (ref. 86) noted, for example, that the large crater rim had an eroded appearance. In the absence of running water and temperature extremes, the only imaginable weathering and erosional mechanisms that can be envisioned are chemical weathering by volatiles, wind erosion, gravity transfer, and erosion by secondary impact. Chemical weathering by volatiles is well known on Earth and similar decomposition may be effective on Venus, especially at the surface temperatures that exist there (747° ±20° K; ref. 154). If primary rocks are derived from the mantle from time to time, or if unweathered rock surfaces are exposed by active surface processes, they will be weathered with consequent removal of volatile constituents from the atmosphere. The rates of production of new surfaces and removal of weathered debris are the factors that control the degree to which surface rocks are weathered and the extent to which volatile constituents have been removed from the atmosphere. The rate of production of primary rocks is unknown, but if the many craters observed are indicative of an ancient surface age, as is suspected, the rates of production may have been quite low over the last 3×10^9 years. If this is the case, and if effective erosional processes are absent as is discussed immediately below, then chemical weathering has not been a major factor in modifying either the landscape or the atmospheric composition over the last 3×10^9 years.

Wind erosion may not be an effective erosional mechanism, considered on a planetary scale. Analysis of Venera-8 data by Ainsworth and Herman (ref. 21) indicates that winds near the surface have velocities of the order of 0.1 m/sec or less. Threshold velocities for initiating grain movement are undoubtedly low, approaching that of a running water regime on Earth (as discussed in section 6.1.3.4). Although planet-wide dust storms or extensive sand seas are unlikely under these conditions, aeolian transport is possible. Measurements of wind velocity at several areas on the surface where topography is known would do much to resolve the question of the possible role of aeolian processes in shaping the Venusian surface. Surface wind velocities of 3.5 m/sec were reported by Venera 9 after this text was prepared. If wind velocities of this magnitude are verified, aeolian erosion and transport is more effective and important than has been recognized previously.

Gravity transfer is possible on steep slopes, but mass movements of debris on slopes less than the angle of repose would be much less extensive than on Earth, where freezing and thawing of pore water and swelling and shrinkage caused by wetting and drying are important factors contributing to such movement. The main weathering mechanisms thus may be chemical decomposition or mechanical disruption produced by impact processes. The latter, however, may be substantially different from that on the Moon. The massive atmosphere of Venus precludes the formation of primary craters with diameters less than about 1 km. Most of the regolith of lunar mare areas, averaging 4-5 m thick and generated during the last 3×10^9 to 3.8×10^9 years, was derived predominantly from craters of this forbidden size (ref. 155). Furthermore, the fine-grained character of all lunar regolith results from repetitive impact of the low-mass component of this class of impacting bodies. If impact on

Venus has been responsible for the craters observed there, as is highly possible in view of the extensive record preserved on Mars, Mercury, and the Moon, large quantities of fragmental debris have been produced and spread over the surface. The character and distribution of that debris will be substantially different from the lunar case, however. The distribution of ejecta launched in ballistic trajectories will be more restricted than on the Moon because of the higher gravity field and because of atmospheric drag. However, the presence of an atmosphere may engender the formation of base surge mechanisms that may provide for extensive near-surface transport of debris away from the source craters. The net result of the interactions of these mechanisms would be extensive ejecta aprons and flow-like deposits of debris surrounding each crater. Abundant quantities of melt rock can be expected in the deposits of the larger craters, probably to a much greater extent than on the Moon because of the high initial temperatures. In fact, flanking deposits of the large craters and basins may consist of coarse ejecta, large flow masses of melt rock, and blankets and lobes of thermally annealed ignimbrites. The melt rock flows and ignimbrite sheets may have surfaces altered by fumarolic type activity, which is common, for example, on the surface of terrestrial ignimbrites, but the general surface character probably would be more rubbly and coarser grained than lunar ejecta aprons of comparable age.

The formation of large craters not only would produce large constructional deposits but also would provide a mechanism for possibly extensive erosion outside the regions of the continuous crater deposits. Large projectiles launched into ballistic trajectories with sufficient velocity would impact the surface to produce secondary craters and additional fragmental debris. Thus, cratering by primary and secondary impact may have provided the most effective mechanisms for erosion and transportation of the Venusian surface. If the cratering took place predominantly early in the history of the planet as for the Moon and Mars, most of the erosion also took place then. Subsequent erosive activity would have been minimal, perhaps throughout the last 3×10^9 years. The distributions of craters observed on the surface of Venus suggest that this interpretation is correct provided the craters were formed by impact.

A great deal of evidence regarding the role of impact in shaping the surface could be gained from radar imaging obtained from orbit. Local views of the surface provided by imaging experiments on landed spacecraft would contribute to the appreciation of the full effect of the impact process.

9.1.3 Tectonics and structure - It has been suspected for several years that high radar backscatter from selected regions of Venus may indicate the presence of mountainous or rough terrain. The question remains open, however, whether extensive tectonic or volcanic mountain chains now exist or ever existed. It is now confirmed that one mountain system of moderate size (6000 × 500 × 3 km) exists (ref. 84), that there is at least one long (300 km) narrow (< 35 km) linear feature that may be a fracture or fault system (ref. 86), and that there is a large canyon-like feature, not unlike Valles Marineris in scale (Goldstein, personal communication, 1975). Aside from the knowledge of the existence of numerous craters of various sizes and that the total planetary relief is about 6 km, there is little else known.

Knowledge of the current tectonic state of Venus would contribute significantly to the understanding of its surface evolution and could provide

valuable insights regarding the thickness and rheological properties of the lithosphere, properties that cannot be measured currently because of the technological inability to maintain long lifetime geophysical stations on the surface. Clearly, an observational approach is indicated. Mapping of surface morphology over large areas of Venus using either Earth-based or orbital radar-imaging capabilities would provide the most immediately available evidence that could be used to understand the evolution of the surface. For example, do shield and basin areas exist, analogous to terrestrial continents and ocean basins? Do mountainous regions have the morphology of volcanic piles, fault blocks, or folded belts? Are these spatial relationships between structural provinces indicative of plate motions? These and other questions could be answered using such an approach. Further, if mapping is combined with chemical analyses of recognized classes of morphological units (in-situ x-ray fluorescence and γ-ray spectrometric measurements are technologically feasible now), a giant step will have been taken toward achieving an understanding of Venusian evolution.

9.1.4 Volcanism - Volcanic activity probably took place during the early history of Venus, but there is no evidence of later or present-day activity. The craters observed on the surface have been assumed to be of impact origin, but volcanic origins cannot be ruled out. Even if those craters formed by impact, triggering of extensive volcanic activity could have occurred in view of the high temperatures expected at modest depths. If volcanic activity has taken place, the nature of the eruptive mechanisms is unknown. The very dense atmosphere of Venus may affect significantly the vesiculation rate of ascending magmas. This, together with lack of knowledge of magma temperature, composition, and volatile content, makes any interpretation highly speculative. More information on surface morphology may provide clues as to magma viscosity, whether lava was erupted from central vents or from fissure systems, or whether flow features are associated in time and space with large craters and basins, but without compositional information (x-ray fluorescence, γ-ray spectrometry) the interpretation of volcanic processes and history will be frought with difficulty. Clearly, surface imaging followed by strategically sited landers for obtaining compositional information would constitute the most rational exploration plan.

9.. Surface properties - The above discussions lead to the conclusion that a complex suite of igneous and/or metamorphic rocks and impact products of various types may exist everywhere at the planet's surface. They may be overlain by a mantle of weathered debris, but accumulations of sedimentary rocks having significant thickness are unlikely. The properties of the weathered mantle are of interest in view of possible surface exploration. The possible role of chemical weathering has been discussed briefly, but how widespread or thick such a mantle (regolith) may be is problematical. The physical properties of the supposed regolith are difficult to interpret. There is no reasonable way to infer grain size or other properties that might depend on surface-temperature modification of such material. Whatever the grain size, surface temperatures preclude the existence of hydrous minerals. If the grain size is coarse (mean size of gravel or coarser) and a fine fraction is negligible, the density of such a regolith could be as measured (1.5 gm/cc) but other physical properties would be substantially different from those of a fine-grained soil.

If mechanisms existed to produce a regolith of finer grain size, and a significant fraction was very fine, the high surface temperatures (and atmospheric pressure) may have caused sintering, again modifying its physical properties. Thus penetration resistance is unknown. It may vary from that of a loose soil, about 5 N/cm^2 with a gradient of 5 N/cm^3 (determined using a hand penetrometer with a 30° cone) as measured on the Moon, to that of a basalt or granite (in the absence of a significantly thick soil).

Thermal properties are unknown also. Thermal conductivity may range from that of dry terrestrial soils to that of granite at 500° C, $0.5\text{-}5\times10^{-3}$ cal/cm-sec-°C. For a Venusian regolith, the best single estimate is 1×10^{-3} cal/cm-sec-°C. The heat capacity of surface rock or soil probably would be between 1 and 1.2 J/gm.

Measurements by several physical properties of surface soil or rock could be obtained by monitoring the dynamic characteristics of a landing spacecraft or by employing spacecraft-mounted squib or spring-driven penetrometers. Additional information could be obtained from surface visualization experiments in a manner similar to that achieved by the Surveyor missions. Seismic wave velocities in the upper tens of meters and thus indirect knowledge of the physical properties of the materials there could be obtained from an active seismic experiment.

9.1.6 Summary: Most likely properties of Venus -

(1) Venus most likely has a core-mantle-crust structure.

(2) Rocks of granitic composition exist at the surface. Their areal extent is unknown as is their origin. An ultimate origin by igneous differentiation is probable.

(3) Venus is undoubtedly seismically active, but comparisons with the Earth or Moon in terms of energy release, depth of focus, etc., cannot be made at this time.

(4) Venus may or may not have a weak magnetic field. Remnant fields are probably absent because of the thermal regime.

(5) Rock crystallization ages may range from very ancient to very youthful. Ages of rocks in highly cratered terrains may reflect the time of intense bombardment as on the Moon. Gas retention age dating is probably impossible because of the prolonged exposure of the rocks to high temperatures.

(6) Extensive oceans probably never existed on Venus. Transient seas may have existed early and some sedimentary rocks may have been produced and later inundated or engulfed by igneous rocks. Remnants of sedimentary strata could possibly exist as metamorphic rocks, but extensive metamorphic belts are unlikely.

(7) Fold mountains may or may not exist. Fault block mountains probably are present and volcanic ridges may be present as well. Substantial crustal relief is sustained, but whether or not crustal loads are gravitationally compensated is not known.

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(8) Impact processes have probably produced large quantities of fragmental debris, masses of melt rock, and ignimbrite sheets. Ejecta probably are distributed less widely about source craters and are composed of coarser fragments than they are on the Moon. Complex flows of impact melt may emanate from or surround the large craters, mimicing extrusive lavas. Sheets and flow lobes of thermally annealed ignimbrites may spread further outward, having been transported in gas-charged, ground-hugging flows akin to base surges.

(9) Volcanic rocks likely are present at and near the surface. Their distribution, mode of occurrence, and times of eruption are unknown. Their physical characteristics may be somewhat different from terrestrial rocks of similar composition. The atmospheric pressure and magma volatile contents may significantly alter vesiculation and eruption mechanisms.

(10) Weathering mechanisms on Venus may include chemical decomposition produced rapidly at elevated temperatures by the interaction of atmospheric gases with surface rocks and mechanical disintegration produced by secondary impacts. The thickness of the weathered mantle may vary.

(11) Agencies of transport may be ineffectual in redistributing or concentrating weathered debris. Winds may have sufficient velocity locally to move debris, but unless near surface winds have velocities greater than those presently suspected, large-scale dust movement of sand-sea formation appears unlikely. Downslope movement of debris on steep slopes undoubtedly takes place by gravity transfer aided by seismic shaking, but movement by creep on lower slopes is unlikely. Impact and possibly volcanic processes may have been more responsible than any other mechanisms for transporting debris long distances over the surface.

(12) Physical properties of surface materials cannot be estimated with any degree of precision. Density may everywhere be near 1.5 as was measured by Venera 8, but, more likely, it may vary as different soil and rock surfaces are sampled. Penetration resistance may vary from place to place as well. Penetration resistance of Venusian soils may be higher than that of soils on Earth. Possible values range from an unexpected minimum of lunar-like (5 N/cm^2 with a gradient of 5 N/cm^3) to an upper limit defined by penetration resistance of granite. Thermal conductivity may range from that of a dry soil, about 0.5×10^{-3} cal/cm-sec-°C, to that of granite, about 5×10^{-3} cal/cm-sec-°C, at Venusian surface temperatures. A best single estimate would be for a sintered soil, 1×10^{-3} cal/cm-sec-°C. The heat capacity would lie between 1 and 1.2 J/gm and seismic velocities in possible soil layers would be a few hundred meters/sec.

9.1.7 Improvements in the data base - Following the Pioneer Venus, VOIR, and additional Venera missions, and after results of improved Earth-based radar-mapping are obtained, the following information may have been acquired:

(1) Scale and distribution of surface relief (shield and basin structure?)

(2) Presence or absence (and if present, the structure of) mountain chains and linear valleys

(3) Cratering record and relative ages of widespread surface units

(4) Presence or absence of volcanic centers or regions

(5) Content of U, Th, and K and possibly other elements in surface rocks at one or more localities

(6) Density of surface materials at one or more localities

(7) Axial symmetry of mass distribution, spin vector direction, polar motion, and, at least, the lowest-order gravitational harmonic

(8) Evidence or lack of evidence of surficial change indicative of surface transport

(9) Presence or absence of hot spots with positive anomalies > 10° K (at best)

(10) First-order approximations of the planetary thermal flux

(11) Correlation or lack of correlation of dielectric constant with morphological features or map units

(12) Surface wind velocities

(13) Morphological characteristics of selected surface features with resolution of about 200 m that provide evidence of surface processes

While the above information would greatly enhance our knowledge of Venus, it would not provide answers sufficiently definitive to determine the present state and past history with the rigor required for comparative planetological studies. It is of the utmost importance that similarities and differences between Earth and Venus be known as completely as possible so that the divergent evolutionary paths of the near-twin planets can be understood. The greatest lack of knowledge in the 1980's will be in geochemical properties. That information can be obtained only by in-situ analyses of different crustal units.

9.2 Instruments and Candidate Payloads

A general approach to exploration must be adopted at the outset so that instruments and candidate payloads for surface lander missions can be proposed on a rational basis. The surface environment of Venus is so severe that landed instruments must be encapsulated, isolated from the high temperature and pressure. Further, to ensure meaningful lifetimes, heat shorts must be kept to a minimum. Even then, using current technology, landers will have surface lifetimes measured in hours in the best case. The ultimate goal in Venusian surface exploration may be the landing of a few long-life capsules on the surface. Those landers might include such experiments as passive seismometry, solar tide measurement, mineralogical analyses, and possibly age-dating experiments. The

technological capability required to develop long-lifetime landers of this type does not exist now and this kind of mission will not be discussed further here. The technological capability does exist, hc /ever, to develop and instrument short-lifetime landers (~1-hr survival) and medium-lifetime landers (10-20-hr survival). In concept, short-lifetime lander missions would be designed to place multiple, small payloads with limited measurement capability in selected terrain types, whereas a medium-lifetime mission would involve the landing at one site of a single capsule, instrumented with an array of instruments that would make a variety of measurements.

Short-lifetime landers could be any of the following: (1) probe landers that would make atmospheric measurements during descent and continue to function for up to 1 hr after landing, during which time one or a few geochemical experiments are performed; (2) penetrators that would pass through the atmosphere, perhaps making limited measurements on descent, penetrate the surface and make a limited number of geochemical measurements; or (3) dropsondes, released from balloons, that would reach the surface and survive sufficiently long to make one or a few geochemical measurements.

This study indicates, for a variety of reasons, that balloon missions are of lesser priority (and technological feasibility), currently, than lander missions. Dropsondes, therefore, were not considered as likely candidates for early landers. The concept must be retained and examined thoroughly, however, for at some stage in the exploration of Venus, a balloon mission may be carried out. The dropsonde approach would provide a unique capability for placing small geochemical packages in tightly targeted terrain units.

The penetrator approach was examined more thoroughly. This preliminary study showed, however, that there are several severe problems that may prohibit their use on Venus. First, the dense atmosphere so limits the free-fall velocity that penetration by small penetrators of reasonable design (<1 m long) is probably precluded for most probable surface materials. Thus, with the uncertainty as to the physical properties of surface materials, there is no assurance that small penetrators could implant instruments successfully. Further, because the inside diameter of any penetrator is small to begin with, only a limited thickness of insulation and a small volume of phase change material can be carried. Consequently, lifetimes of small penetrators would be measured in minutes. To assure penetration and survival for reasonable times, penetrators would have to be of such length and mass that there would be no capability of implanting numbers of them on the same mission. For these reasons, this approach was abandoned in these considerations.

It does appear possible, on the other hand, to design atmospheric probes much like the small probes of Pioneer Venus that could survive on the surface for reasonable times, up to 1 hr. This approach was selected in this study as the most likely candidate for delivering short-lifetime landers to multiple sites during a single mission. In further discussions in this study, therefore, <u>short-lifetime landers are designated as probe landers</u>.

Medium-lifetime landers can be designed that would survive for 20 hr or more on the surface. All designs that would assure such survival are based on the pressure vessel or capsule concept. For ease of discussion, therefore,

medium-lifetime (10-20 hr) landers are henceforth called capsule landers. This type of lander has the weight, volume, and survival time such that a rather wide variety of measurements can be made.

Two approaches have been identified that appear useful in initial surface exploration of Venus: multiple-probe landers and single-capsule landers. Each approach has advantages and disadvantages that must be considered carefully before a mission is recommended. The approach taken here, therefore, is to consider candidate experiments that can or might be performed using both approaches and then to discuss the possible use of each (section 9.3).

Both approaches are limited, certainly, in terms of the kinds of experiments that can be performed. A number of experiments normally considered as prime candidates for missions to the inner planets are excluded, either by the time available for measurement or by the necessity for encapsulation. It appears impossible to perform heat flow, passive seismic, or α-backscatter experiments on early landed missions, for example. A list of experiments that can be designed now and that would contribute to the solution of major questions that will remain unanswered in the 1980's is given below. A short description of each experiment follows on succeeding pages.

Experiment	Primary applications	Mission PL	Type CL
(1) γ-ray spectrometry	Obtain evidence of differentiation rock types and possible weathering mechanisms	?	+
(2) X-ray fluorescence	Obtain evidence of differentiation, rock types (including possible sedimentary rocks), and possible weathering mechanisms	+	+
(3) Landing dynamics	Measure surface physical properties	+	+
(4) Surface visualization	Determine physical state and textural properties of surface materials	0	+
(5) Spectral reflectance	Obtain evidence of rock types, history, and state of surface oxidation	0	?
(6) Wind velocity, pressure, and temperature	Assess possible importance of aeolian processes	±	+
(7) Gas chromatography	Identify surface volatiles	0	+
(8) Active seismic experiment	Measure near-surface physical properties and structure	0	?

PL = probe lander, CL = capsule lander, + = yes, 0 = no, ? = questionable, and ± = in part.

9.2.1 γ-ray spectrometer - This highly desirable experiment would measure the concentrations of U, Th, and K in surface rocks and thus supply a significant amount of information about the extent of planetary differentiation and the kinds of rocks expected to contain the measured levels of radioactivity. The experiment requires no feedthrough to the surface and thus introduces no heat shorts. The design is not hardened, although one could be selected now

using a NaI-photomultiplier scintillation detector. A significant reduction in weight could be achieved by using solid-state detectors needing no cryogenic cooling. The state of the art and rate of progress in developing such detectors or arrays of detectors is such that this is highly probable. In addition to the scintillation detector, associated electronics include a high-voltage supply, a low-voltage supply amplifier, pulse-height analyzer, intermediate storage, and routing logic. In a capsule lander, some of the electronics could be shared by other experiments. Tradeoffs are required between the numbers of channels, resolution, and counting times. This suggests that the final selection will be somewhere between the extremes of the Venera-8 system (60 channels, with a total data-collection time of 42 min, and a 512-channel analyzer with a data-collection time approaching 10 hr). The selection depends, in large part, on mission duration. A 64-channel system may be acceptable for a 1-hr maximum lifetime mission whereas a 128-channel system may be optimum for a 20-hr mission.

9.2.2 X-ray fluorescence - X-ray fluorescence is a standard laboratory technique for analyzing quantitatively for elements of atomic number 10 and larger. Such an analysis of Venusian surface dust would provide invaluable data for determining the composition of surface rocks and soils, and hence the rock types present and the extent to which the planet has been differentiated. A number of techniques are available. The one suggested here is an existing design. The instrument consists of externally mounted proportional counters with sample-window housings supporting thin, concave beryllium-foil windows. Soft-x-ray sources (Fe^{55} and Cd^{109}) located inside the sample-window housing irradiate the sample window. Dust adhering to the window absorbs the incident radiation and emits characteristic x-rays, some of which pass the second window into the gas proportional counter and produce current pulses. Current pulses are fed through the pressure shell to internally located electronics. The instrument has been designed to operate at 100 atm and at temperatures up to 500° C. It provides a system for the chemical analysis of surface dust with only minimal heat shorts. If it is carried on a capsule lander in combination with a spectral reflectance analyzer, electronics, primarily the multichannel analyzer, could be common to the two experiments.

The problem of ensuring that dust is collected on the concave window may or may not be significant. The exterior unit could be located close to ground surface near a landing pad on the capsule lander where dust is likely produced on landing, or even dropped to the surface so that the slightly recessed windows are at the immediate surface where the surface agitation produced by the emplacement would provide for the deposition of a layer of dust on the window with a thickness in excess of 1 μm (the minimum for good measurement). An additional possibility is that of directing a jet of pressurized CO_2 at the surface so that ejected dust is deposited on the sensor. The problem is more severe on a probe lander and design studies would have to be undertaken to determine whether the lander could be oriented after impact or whether dust deposition on the counter windows would be probable.

9.2.3 Landing dynamics - surface physical properties - Physical properties of the surface can be determined to varying degrees of precision, depending on the instrumentation selected. Accelerometers on probe landers or on capsule landing pads deployed in a manner similar to those of the Surveyor spacecraft

could provide significant information regarding the properties of surface materials to a depth of several centimeters. An extreme case for a capsule lander would employ an exterior-mounted, rocket-driven penetrometer. An intermediate technique could use spring- or squib-driven penetrometers rigidly mounted on one or more of the footpads. Current thoughts based on the priority assigned to this information suggest that the latter technique is most appropriate for the capsule. Weight, power, and bits of information are uncertain. Estimates for a single accelerometer are 100 gm, 0.5 W with a maximum of 8000 bits of information. For a two-penetrator system, those values would be doubled.

9.2.4 Surface visualization (TV) (capsule lander only) - Surface imagery of the immediate landing area would provide a wealth of information regarding the nature of the immediate surface; is it solid, rock strewn, or soil-like? If solid or rock strewn, some insight could be gained regarding the texture of the rock(s). If soil-like, the general nature of the grain-size distribution could be determined and, if the imagery includes one of the landing pads, estimates of angle of repose, angle of internal friction, and cohesiveness could be obtained. The imaging experiment would require an optical window through the pressure vessel and insulation. If such a window is provided, additional experiments could be conducted using the window. A low-power light source would be required for imaging the immediate spacecraft vicinity (25 W with reflector) and, for more distant views, a flare illumination is required. Power, mass, volume, and data rate can be estimated for a simple system. The mass would be about 5.5 kg; the volume would be about 500 cm^3; and 14 W would be required for camera operation. Each image would produce 972,000 bits. Because of time and bit-rate constraints, extensive imagery is not feasible. First priority is for images of the immediate surface, one including a footpad. Second priority is for images at slightly greater distances, but still only meters away. If this capability is desired, an external mirror is required that can be positioned. The third priority is for images of the surface out to tens of meters. This requirement would require a mast and motor-driven mirror assembly and a flare light source. The latter would add about 3 kg to the mass and would increase the power required (for motor drive) by about 3 W.

9.2.5 Spectral reflectance and IR, UV, and visible flux (capsule lander only) - Adams (ref. 156) points out that spin-allowed Fe^{2+} absorption band occurs in the visible and near-IR diffuse reflectance spectra of most pyroxenes. Wavelengths of the bands centered near 1 and 2 μm vary as functions of pyroxene composition, making possible mineralogical and chemical deductions based on spectral reflectance curves. Typically, pyroxene bands are well developed in relation to absorption features in the spectra of other rock-forming minerals and glass; thus pyroxene often dominates the spectral curves of pyroxene-bearing rocks. Since pyroxenes are abundant in many rocks and since the composition of the pyroxene is useful in classifying those rocks, knowledge of the pyroxene composition in consort with an x-ray fluorescent analysis of surface materials would provide much additional information regarding the rock types on the Verusian surface. Telescopic spectra of the Moon and other solar-system objects have been interpreted in terms of their pyroxene content/composition mixed with other minerals and/or glass; there is good reason to anticipate that an instrument could be constructed for making measurements on the surface of Venus, especially if a window through the pressure vessel is provided. Such a

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device is only envisaged at present. It would require that a package be dropped to the surface containing an aluminum oxide hemisphere with a light source (to provide diffuse radiation) and a collector in the hemisphere with a fiber optics bundle or other optical path to the window. Inside the window, a flip-in mirror would direct the light to a spectroflectometer. Precise mass, volume, power, and data requirements cannot be given. A multichannel analyzer would be required and, in a large capsule, could be shared with other experiments. Additionally, through external switching of TV imagery mirrors, the spectral character (and flux) of incident planetary thermal and solar radiation could be determined with the same equipment.

The development of an instrument such as that suggested would require considerable effort. It is the least firm of the candidate experiments, but there is no reason to suspect that the development would pose insurmountable problems. If a window is provided for imagery, every effort should be made to use that window for additional experiments. Spectral reflectance is the most meaningful experiment that could make use of such a capability, and it should be considered as having considerable potential. Additional supporting research and technology is required to evaluate the technique.

9.2.6 Wind velocity, temperature, and pressure - All these properties may be measured and are scientifically valuable. Minimal heat shorts would result from feedthroughs. Development of temperature and pressure sensors would pose no serious problems. Because each measurement would produce only 8 bits of information and, because measurements once an hour for an estimated survival time of 20 hr would produce only 160 total bits per sensor, these experiments would pose no data problems. A hot film anemometer or other device for wind-velocity measurements would produce 8 bits/sec during measurement. Measurements must last at least 10 sec. Thus, 80 bits per measurement would be produced. Measurements once an hour for a 20-hr lifetime would produce only 1600 total bits. Temperature and pressure measurements are possible on both probe and capsule landers. Measurement of wind velocity is not a candidate experiment for probe landers.

9.2.7 Chromatography (capsule lander only) - A hybrid gas chromatograph for the analysis of near-surface volatiles could be developed. The operating temperature of such an instrument would be hardly more limited than that of any other sensor.

The primary signal is acquired by three functional components, namely, a sampling valve array (about six miniature valves), a steel column packed with the analytical sorbent, and a detector. The valves would probably be the foremost problem. Presently existing designs will not operate above 180° C. The detector would very likely have to be a beta-ionization type that should not require too much development, and it should tolerate some fairly high temperatures as well as thermal instabilities. Column packings can be of some organic variety, but there are also some inorganic materials for choice.

The types of unknown gases and vapors that could be measured by the chromatograph are the stable molecules such as water. Ions, radicals, metastables, or reactive species could not be detected.

The sample sizes one might project would be of the order of 1 to 10 μM. It is apparent that the mass of the gas sample would be rather small, even in the event that one should plan to acquire a small multiple for the purpose of equilibration or purge. The lower limit of detection would be typically 10 ppm of each detectable component in the atmosphere. The valving system might require a reduction orifice lowering the pressure to a dynamic value of 20 bars for sampling, which would result in a typical detection limit of 50 ppm. A successful design would aim at the individual measurement of vapors of higher molecular weights than those for which the present atmospheric analyzers are intended. The longer operating time of the lander instrument would give the advantage of slower carrier gas-flow rates and increased sensitivity. The latter could be much better than 50 ppm for certain detectors and classes of unknown materials.

9.2.8 Active seismic experiment (capsule lander only) - An active seismic experiment could be performed on the surface. In its simplest form, with a single lander, a single geophone could be included in the instrument capsule, and small explosive charges (28 to 57 g) could be propelled to calculated short distances on the surface. Preliminary calculations suggest that charge-to-sensor distances of 10, 25, 50, and 75 m may be adequate to characterize surface materials either for a lunar mare-like regolith case (100 m sec^{-1}/1200 m sec^{-1}) with upper-layer thicknesses up to 15 m or for a case where a higher-velocity upper layer (up to 20 m thick) lies on a rocklike substrate (250 m sec^{-1}/1200 m sec^{-1}). With a single geophone and with the small number of charges possible (3 to 4), only limited information regarding seismic-wave velocities and near-surface structure could be obtained, even if precise times of detonation and distances from the spacecraft are obtainable. Note that the very shallow structure of the lunar surface, to a depth of 25 m, was not well documented by seismic experiments where rather sophisticated procedures were followed. The results obtained still are unresolved and greater reliance is placed on results obtained using other methods.

Nevertheless, this experiment would provide the only capability of determining the bulk physical properties of surface materials to depths of tens of meters. The most significant problems envisaged are propelling explosives to known distances across the surface in an environment where the handling of explosives is extremely difficult, and ensuring collection and transmission of detailed seismograms. Because of its importance, this experiment should be included in lander mission planning regardless of the problems that may be encountered. It may be necessary, in fact, to consider specially designed multicapsule lander systems to provide a seismic exploration capability whereby a main capsule that includes a geophone and smaller satellite capsules that contain the explosive charges are landed in a predetermined geometric array.

9.2.9 Summary of surface experiments - A number of experiments were discussed above that would contribute significantly to our knowledge of Venus if they are carried out at the surface. All or most of those listed could be performed using a capsule lander. A summation of the candidate instruments for such a lander is given in table XXXIII that includes preliminary estimates of weight, volume, power, and data requirements. Information in the table can be applied to probe lander systems as well by selecting appropriate experiments. Note, however, that additional atmospheric experiments not given in that table must be considered as well.

TABLE XXXIII.- CANDIDATE INSTRUMENTS SCIENCE PAYLOAD/VENUS CAPSULE LANDER

Instrument	Weight (gm)	Dimensions, large packages (cm)	Volume (cm^3)	Power	Bits/Sample	Samples/Mission
γ-ray spectrometer	1000-2000* (including electronics)		120-400*	200 mV-2 W	10,000 (max)	2 minimum
x-ray fluorescence analyzer	2223* (including electronics)	17.8 × 20.3 × 7.6* (including electronics)	205 (exterior) 2753 (electronics)	2 W	100,000 (max)	2 minimum
Temperature	100		16	0.5 W	8	20
Pressure	100		20	0.2 W	8	20
Anemometer	230		33	1 W	80 (8/sec/10 sec)	20
TV camera	5443	10.2 × 16.5 × 30.5	5113	14 W	972,000	4 minimum 10 maximum
Optics	680					
Optional mast + motor	3175			3 W		
Spectral reflectance (+ photometer) either						
a) directional or	800	7.6 × 7.6 × 15.2*	878	5 W	100,000 (max)	2 minimum
b) diffuse	1600	7.6 × 7.6 × 15.2*	878	5 W		2 minimum
Landing dynamics either						
a) single accelerometer or	100	---	---	0.05 W	8000 (max)	1
b) two penetrometer system	200	---	---	0.1 W	8000 (max)	2
Gas chromatograph (single column) including electronics	2500	20 × 20 × 10	4000	20	15,000	2-6 (2 per hr)
Active seismic experiment						
Shock & seismic wave sensors & electronics	400			1 W	Seismic = 40, 8-bit samples/sec/30 sec Shock = 80, 8-bit samples/sec/4 sec	
Explosive charges and launcher	850	(external)	(external)			
Total	1250			1 W	1.2×10^4/experiment	4 experiments

*A number of weight, dimension, and volume figures include electronics that could be shared. A multichannel analyzer could be shared by Y-ray, x-ray, and spectral reflectance.

9.3 Experiment Sets and Mission Types

Consideration must be given as to whether the first surface exploration of Venus would be accomplished best by a single-capsule lander, by multiple probe landers, or by a combination of the two. This is a complex question that has not been resolved for several reasons. First, the probable scale or extent of apparent surface heterogeneity cannot be estimated now, but it will be known better before a lander mission will be launched. Second, there is no firm evidence yet that definitive geochemical measurements can be made using probe landers. Third, there is no current framework of long-range planning that provides a basis for assessing the importance of obtaining information other than that of a geochemical nature that might impact the design of future landers.

Preliminary estimates of surface heterogeneity are extremely important, first in determining the type of mission that would offer the greatest scientific return and, second, in selecting critical landing sites. Radar imagery of very large regions with resolution of at least 1 km must be obtained and analyzed as quickly as possible to provide the necessary inputs. Results of analysis of such imagery may show, for example, that the surface is rather homogeneous with few recognizable terrain types that might be indicative of compositional variation. If this is the case, and knowing the locations of analyses made previously by Venera landers (perhaps three by 1976), it might be more important from a scientific standpoint to investigate a single site in greater detail than to look for possible lateral variations. On the other hand, analysis of radar imagery may demonstrate that the surface is complex, either in terms of a large number of terrain types or with regard to the distribution patterns of a smaller number of units. In either of these latter cases, it might be most advisable to determine the composition of as many terrain types as possible using multiple probe landers. In view of the importance of this information in selecting the most meaningful mission, and since the information will be forthcoming though perhaps late in the mission planning sequence, it is recommended that current planning proceed on the assumption that a combined probe-capsule mission will be carried out until a time when more definitive criteria are available with regard to both surface heterogeneity and the geochemical measurement capability of probe landers.

The question of whether definitive geochemical measurements can be made using probe landers has not been answered. If instrumentation is limited to γ-ray counting with a limited number of channels and short counting time, definitive answers would not be obtained if rocks with low radioactivity are encountered. Measurements at the landing site of Venera 8 suggest the presence there of rocks with radioactivity contents similar to those of terrestrial granitic rocks. If these are present everywhere on the surface, that would be revealed by a multiprobe mission with γ-counting capability, but if a variety of rock types are present with a range of radioactive contents, where some units have lesser contents, the γ-counting system may not have sufficient resolution to document the case. If x-ray fluorescence analyses are possible, on the other hand, this shortcoming does not exist. Clearly, a concerted effort must be made to determine whether x-ray fluorescence analyses can be performed on small-probe landers. The outlook is promising.

Detailed long-range planning of the surface exploration of Venus together with a careful assessment of developing technology are needed to determine whether there is a requirement for a sequence of measurements that would provide inputs necessary for a rational development of successive missions. For example, penetrators were not considered candidates for an initial mission in part because of lack of knowledge of surface penetrability. If an initial mission were to demonstrate that penetrability of surface materials is comparable to that of terrestrial sand, for example, a penetrator 0.6 m long with a mass/cross-sectional area of 0.2 would have an impact velocity of 74 m/sec^{-1} and a nose depth of penetration of 1.5 m. Complete burial of the penetrator would occur. Further, if research on high-temperature electronics demonstrates a probability of developing this capability in the proper time frame, long-life penetrators could be developed where contained instruments could be exposed to the thermal environment. Given this set of circumstances, the preferred sequence of exploration might be to make a large number of measurements at each landing site in a few terrain units using capsule landers and then explore the complete surface diversity with numerous penetrators, perhaps launched using the shuttle capability.

Clearly, several major questions need to be answered before a rational decision can be made as to whether an initial lander mission should use probe or capsule landers or a combination of the two. It is recommended therefore that the combination mission be considered during the next few years, during which time studies are carried out to answer the critical questions. The first studies should determine (1) the feasibility of performing x-ray fluorescence analyses on probe landers, (2) the time frame when imagery over extensive areas of the surface of 1 km and 200 m resolution will have been obtained and analyzed, and (3) the most desirable sequence of surface missions in a long-term program taking into account probable developments arising out of long lead-time research.

9.3.1 Experiment sets on a capsule lander - Experiments listed in table XXXIII can be grouped into three sets: surface chemistry, physical properties, and atmospheric properties. The surface chemistry set provides three techniques that are unified in the total goal but represent diverse approaches designed to give the maximum information possible within the constraints of the mission. The three techniques together with surface imagery will provide abundant evidence for interpreting the extent of differentiation, the rock type(s) common on the surface, possibly whether they are coarse-grained or fine-grained, foliated or nonfoliated, and the extent to which they have been degraded in the surface environment. If there are weight-volume-power-bit constraints limiting the inclusion of all three experiments, γ-ray and x-ray have equal priority. Spectral reflectance is of somewhat lesser ranking.

Physical property measurements can be obtained from imagery and from dynamic measurements. Together these techniques can give information on the physical properties of surface materials to a depth of several centimeters. The active seismic experiment could obtain information regarding the thickness, physical properties, and stratigraphic homogeneity of regolith materials if they are present to any extent.

Near-surface atmospheric properties have not been considered in any detail. Atmospheric gas analysis, for example, was limited to gas chromatograph measurements. Other techniques are possible. The goals of this study are surface property oriented and those atmospheric properties that relate directly to surface processes have been emphasized, wind velocity and near-surface volatiles primarily. The gas chromatograph has been included as an example of one possible atmospheric analysis technique that could be included, depending on prioritization of mission goals. Measurements of atmospheric properties during entry have not been considered in this analysis. Further study should be given to critical measurements that might be included.

The three sets of measurements proposed are generally compatible, and the chances appear good that all or most of the candidate experiments could be carried out on a single mission. Furthermore, the information to be gained would not be compromised or made obsolete by any precursing orbital mission. A Venusian surface experimental package should have a high priority in plans for future space exploration. Because of the unique conditions on Venus where remote measurement of geochemical properties is precluded, spacecraft instrumentation design could be initiated soon.

9.3.2 Experiment sets on probe landers - Experiments to be performed on probe landers fall into two sets: atmospheric and surface (primarily geochemical). Rationale for performing atmospheric measurements by entry probes is given in section 7.0 and is not repeated here. The need for geochemical measurements has been stressed in the foregoing discussions, and it has been suggested there that geochemical measurements that might be performed are limited to γ-ray spectrometry and/or x-ray fluorescence. It has been recommended further that there is a need for study of the x-ray system to ensure that there is a real capability of surface analysis using this technique. It is of considerable interest that there are potential applications of x-ray fluorescence techniques to the study of cloud particulates. Future studies should explore these atmospheric and surface experimental capabilities simultaneously to determine whether cloud particulate studies could be performed without compromising the geochemical measurements.

In addition to geochemical experiments, an accelerometer would be required that would provide evidence of the physical properties of surface materials. Conveniently, an accelerometer is useful for atmospheric physical structure studies. The choice of other atmospheric experiments that might be included on a given mission would depend on available volume-weight-power and data transmission capability, on compatability with geochemical instruments, and on targeting strategy. Surface analyses will have the highest priority in this mission or mission series. Accordingly, the siting of the probes will be fixed by surface requirements. However, tradeoffs are possible to visit atmospherically interesting regions if alternate sites of high geochemical interest are identified. A list of candidate instruments that might be considered is given in section 7.4.2.

9.4 Engineering Considerations

The rationale for various lander mission concepts was developed in the previous sections. The primary concepts considered were large medium-lived landers and multiple short-lived probe landers and combinations thereof. Surface penetrators were also considered but were shelved for future consideration (discussed in more detail later). In the following sections, each lander concept will be discussed, followed by sections describing overall mission design and system technology requirements.

9.4.1 Medium-lived large lander -

9.4.1.1 Mission description: The baseline medium-lived large capsule lander is designed for about a 20-hr operating life on the surface of Venus. This lander consists of an insulated instrumented spheroidal pressure shell with legs packaged in a conical aeroshell similar to that used for Pioneer Venus. The complete entry vehicle is carried by a spacecraft bus during the launch and interplanetary cruise portion of the mission. Upon arrival at Venus, the entry vehicle is separated from the bus after it is aimed properly and enters the atmosphere. Direct entry, instead of entry from orbit, is used to minimize the launch mass, system complexity, and cost. Direct entry also maximizes the amount of insulation and phase change material (and thus lifetime) for a given launch weight; however, landing sites are restricted to the Earth side of Venus in order to transmit the data directly to Earth. After separation, the spacecraft bus enters the atmosphere and is destroyed. Before its destruction, if instrumented, the bus can return atmospheric data to Earth.

After the entry vehicle enters the atmosphere, the aeroshell is jettisoned and the lander falls through the atmosphere to the surface. As it approaches the surface, landing legs are unfolded to cushion the impact and a terminal parachute is deployed to reduce impact speed and to ensure a proper landing attitude. After touchdown, the lander aims its communication antenna at Earth and begins performing the required science measurements. The lander continues to operate until it overheats and fails.

9.4.1.2 Lander conceptual design: The lander conceptual design is shown in figure 47. All the electronics and most of the science are enclosed in a heavily insulated pressure shell to protect them from the high surface pressure and temperature at Venus. The mortars required for the active seismic experiment are mounted internally for the design shown in the figure; later, more detailed tradeoff studies may require that they be placed outside the lander to minimize heat shorts. A mass summary for the baseline design is as follows:

External legs and antenna	15 kg
Pressure shells and structure (1.1-m OD sphere, 0.8 m ID)	86 kg
Insulation	125 kg
Phase-change material	48 kg
Electronics	15 kg
Battery	46 kg
Science	30 kg
Landed mass	365 kg
Aeroshell	180 kg
Mass at entry	545 kg

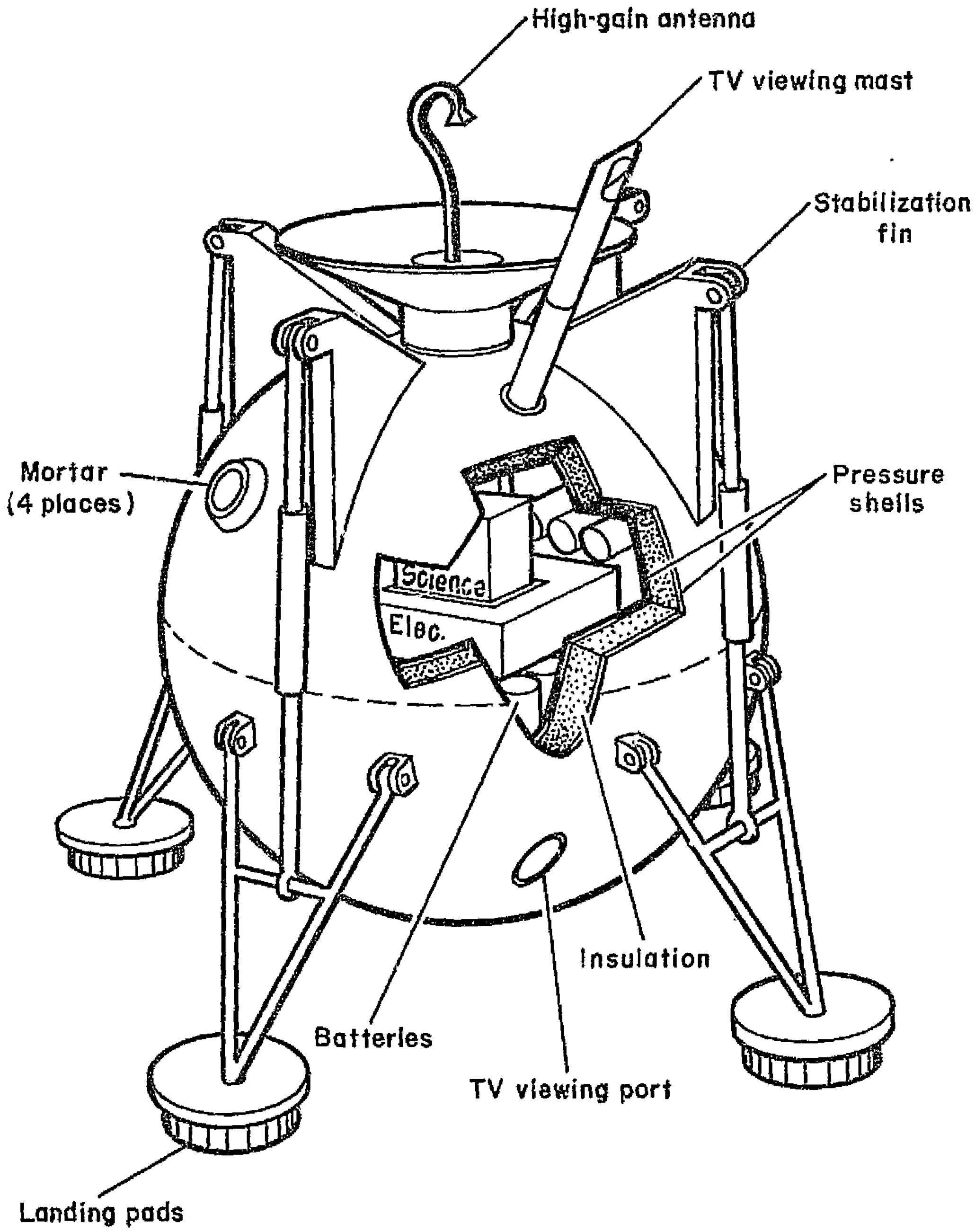

Figure 47.- Venus lander concept.

Communications with Earth are maintained with a two-way S-band system. The uplink from Earth is used as a frequency reference and to carry commands if needed for experiments. The telemetry downlink uses a 5-W transmitter and a 20°-beamwidth, 18-dB external antenna to transmit to Earth. The external antenna is aligned so that Earth is inside its beam after the lander comes to rest on the surface. If the lander is targeted near the sub-Earth point, the antenna is aligned with the local vertical. If the lander is targeted away from the sub-Earth point, the antenna is aligned to an RF signal from Earth. The telemetry system provides 2048 bits/sec to a 64-m DSN antenna at a distance of 58×10^6 km from Earth.

The lander electronics are similar to those used in the Pioneer Venus large probe. Their mass and power requirements are about 15 kg and 33 W, respectively. Lander power is provided by a Ag-Zn battery. The battery is sized to provide 50 W-hr of energy for preentry checkout and to power all electronics and science for 25 hr after landing with a 30-percent safety margin. The total battery design capacity is 2415 W-hr and its mass is 45.6 kg.

Lander thermal protection is provided by a thick layer of external insulation to reduce the heat input from the hot atmosphere and by internal phase-change material to absorb the heat flow through the outer walls as well as the internally generated heat. The major design problem for thermal protection is to minimize heat shorts, which will occur wherever wires, structure, or windows provide a direct path for heat conduction through the insulation. In sizing the baseline lander thermal control system, heat shorts equivalent to 20 cm^2 of steel were assumed. For the design considered here, the thermal protection system is designed to provide 25 hr of operation on the Venusian surface before the temperature rises to 395° K with all electronics and science operating. The electronics are presumed to fail at 395° K. The internal heat generated is 33 W for electronics and 39 W for science. The baseline thermal protection consists of a 14-cm-thick layer of min-K insulation surrounding the lander plus 48 kg of phase-change material distributed within the lander.

9.4.1.3 Lander operational considerations: Since the lander fails by overheating in the severe thermal environment, all measurements are performed quickly and data are transmitted to Earth as soon as possible. The measurement sequence is affected by the power available, the experiment operation cycle time, the telemetry bit rate, and the science rationale. After touchdown, all systems are activated within 5 min. The high-gain antenna is pointed to Earth and telemetry begins. Operating times for the instruments in the science payload are as follows:

Instrument	Time to acquire data	Time to transmit data	Time between samples
γ-ray spectrometer	3 hr	1 sec	Short
X-ray fluorescence	5 min	50 sec	Variable
Anemometer, temperature, pressure	10 sec	1 sec	10 min
TV camera	1 sec	8 min	Variable
Spectral reflectance	5 min	50 sec	Variable
Landing dynamics	---	2 sec	---
Gas chromatograph	30 min	7 sec	Variable
Active seismic	20 min	24 sec	5 min

A preliminary operational sequence is described below and illustrated in figure 48.

The landing dynamics measurements are collected and stored during touchdown and transmitted to Earth after antenna lockup. The γ-ray, x-ray, and spectral-reflectance experiments are activated as soon as possible. Since they share common electronics, they will operate in sequence. The x-ray operates first, followed by the spectral-reflectance and γ-ray experiments in sequence until at least three measurements are made. Temperature, pressure, and anemometer measurements, as well as lander engineering data, are collected each 10 min for the duration of the lander life.

The TV camera and gas chromatograph operate alternately because of their high power demand. The TV system includes an electronic imaging tube to store an image for up to 30 min and to allow its transmission at the telemetry data rate. The TV sequence includes images of a footpad and the x-ray sampling area before and after the x-ray sample window is coated with dust. The TV system requires a mast with optics and controlled mirrors to view the areas around the lander. The TV strategy is to first image areas near the lander and then to image areas farther away. Commands from Earth allow interesting areas to receive special attention. A small lamp is mounted on the mast to enhance the contrast of nearby targets. Pyrotechnic flares are carried, if needed, to enhance contrast for distant targets.

The active seismic experiment is performed late in the mission to avoid possible damage to the lander. Four mortar-launched charges are fired at 5-min intervals and the resultant seismic and air waves are monitored after each charge detonation.

9.4.2 Short-lived small landers -

9.4.2.1 Mission description: The small geochemical probe landers, which are designed for a 1-hr survivability, are similar in many respects to the Pioneer Venus small probes. Several of the landers would be carried on a spacecraft bus and targeted to measure surface properties at several widely spaced locations. After being transported to Venus by a spacecraft bus similar to the Pioneer Venus probe bus, the landers are released from the bus for direct entry on the Earth side of Venus. This option minimizes system complexity and permits direct communications with Earth. After releasing the landers, the bus can be used for scientific experiments, if desired.

After entry the small geochemical probe landers fall to the surface and impact at about 10 m/sec. Prior to impact, the probe afterbody is jettisoned and a spike at the nose of the probe is deployed. The nose spike reduces the impact shock loads, aids in controlling the landed attitude, and provides good coupling between the accelerometers and the Venusian surface.

After landing, four hinged legs are deployed from behind the aeroshell. These legs help orient the lander and have x-ray fluorescence analyzers integrated with their footpads. The lander aims its antenna at Earth and begins performing the required science measurements. The lander continues to operate until it overheats and fails.

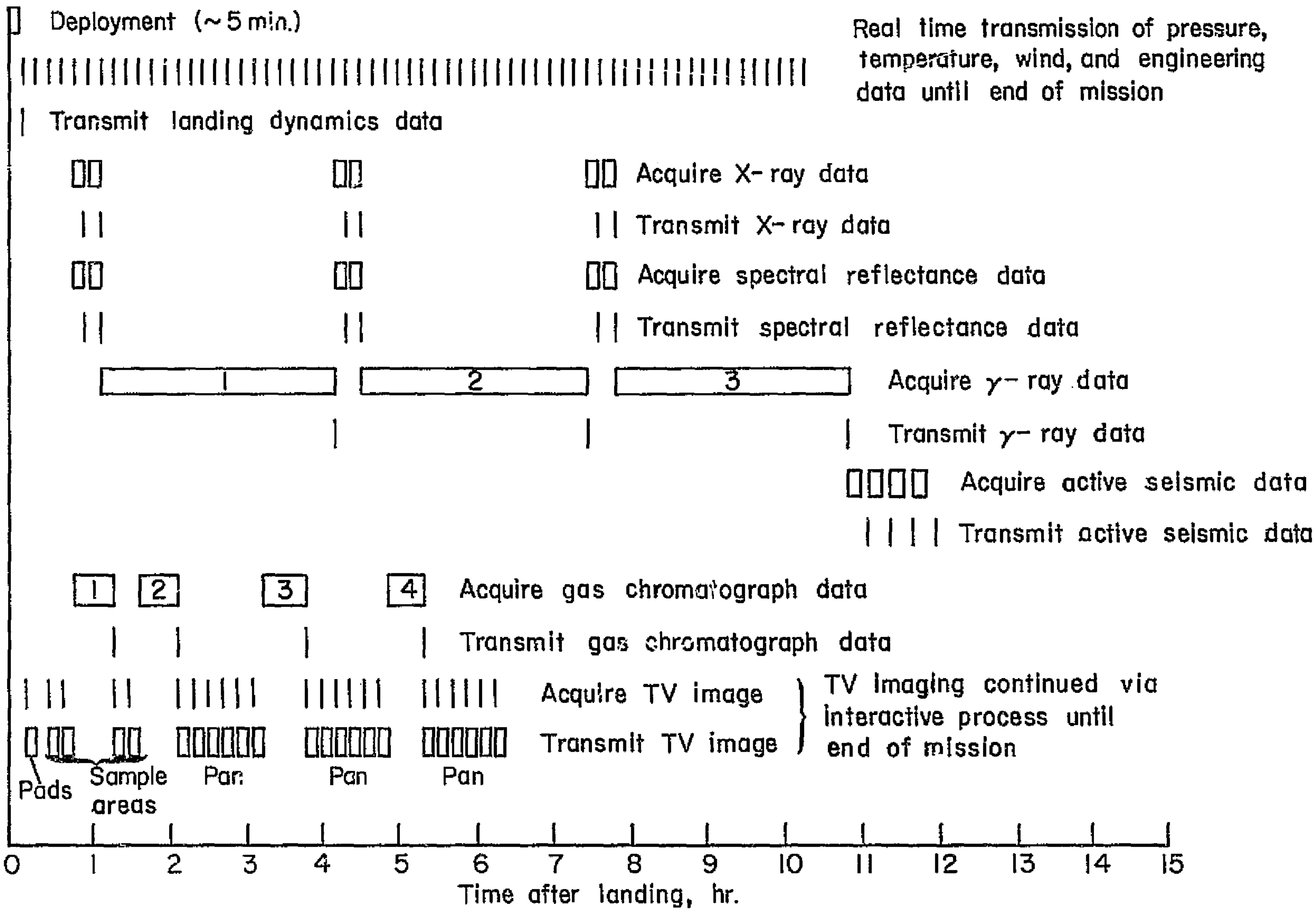

Figure 48.- Lander operational sequence.

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9.4.2.2 Lander conceptual design: Various design options are available for the small short-lived landers. These range from a scaled-down version of the large medium-lived landers (described earlier) to a modified Pioneer Venus small probe (i.e., surface science instruments replacing atmospheric science instruments). For this study, a small probe-like lander is assumed. The baseline lander conceptual design is shown in figure 49.

Science and electronics equipment is contained in an insulated pressure shell that remains integral with the aeroshell. The lander is configured to provide good subsonic dynamic stability to help control the landed attitude. The structure and pressure shell are designed to withstand the impact loads. The nose spike will absorb some of the impact load if the surface is composed of relatively hard rock.

Communications with Earth are maintained with a 10-W, S-band transmitter and a 40° beamwidth, 8-dB cavity cupped helix antenna. The antenna is mounted on the probe so its axis is misaligned 20° from the probe Z axis. After touchdown, the antenna is rotated until maximum signal strength is received at Earth. In this manner, the effective beamwidth of the antenna is doubled. This permits more choice in landing sites and helps to compensate for factors such as surface slopes. This telemetry system provides 400-450 bits/sec to the 64-m DSN antenna at a distance of 58×10^6 km from Earth.

Lander thermal protection is provided by a layer of external insulation to reduce the external heat input and by internal phase-change material to absorb the heat flow through the outer walls as well as the internally generated heat. The major design problems for thermal protection are the heat shorts created by the instrument parts, structural members and wires that penetrate the insulation. In sizing the thermal control system, heat shorts equivalent to 40 cm^2 of steel were assumed. The baseline thermal protection consists of a 4-cm-thick layer of min-K insulation surround the electronics plus 5 kg of phase-change material. This combination provides a surface life of 1-hr before the electronics reach 395° K and presumably fail.

Lander power is provided by a Ag-Zn battery with a design capacity of 250 W-hr that weighs 4.5 kg. The total mass and power of the lander electronics are estimated at 10 kg and 60 W, respectively. Based on scaling the Pioneer Venus probe designs, the small geochemical lander is estimated to have a total mass at entry of 120 kg.

9.4.2.3 Lander operations: The primary instrument set considered for the small geochemical landers consists of an accelerometer and multiple x-ray fluorescence analyzers. An internally mounted γ-ray spectrometer was also considered but not included as a primary instrument for several reasons, including the fact that an additional set of counting equipment would be required in the lander to perform this experiment simultaneously with the x-ray experiment and that the counting time may not be long enough for good recording statistics.

For the baseline lander, an accelerometer is mounted in the thermally controlled equipment compartment and x-ray fluorescence analyzers are mounted on each of the four hinged legs. The x-ray units are pivoted so that they can be positioned on the surface to maintain the proper source-detector geometry.

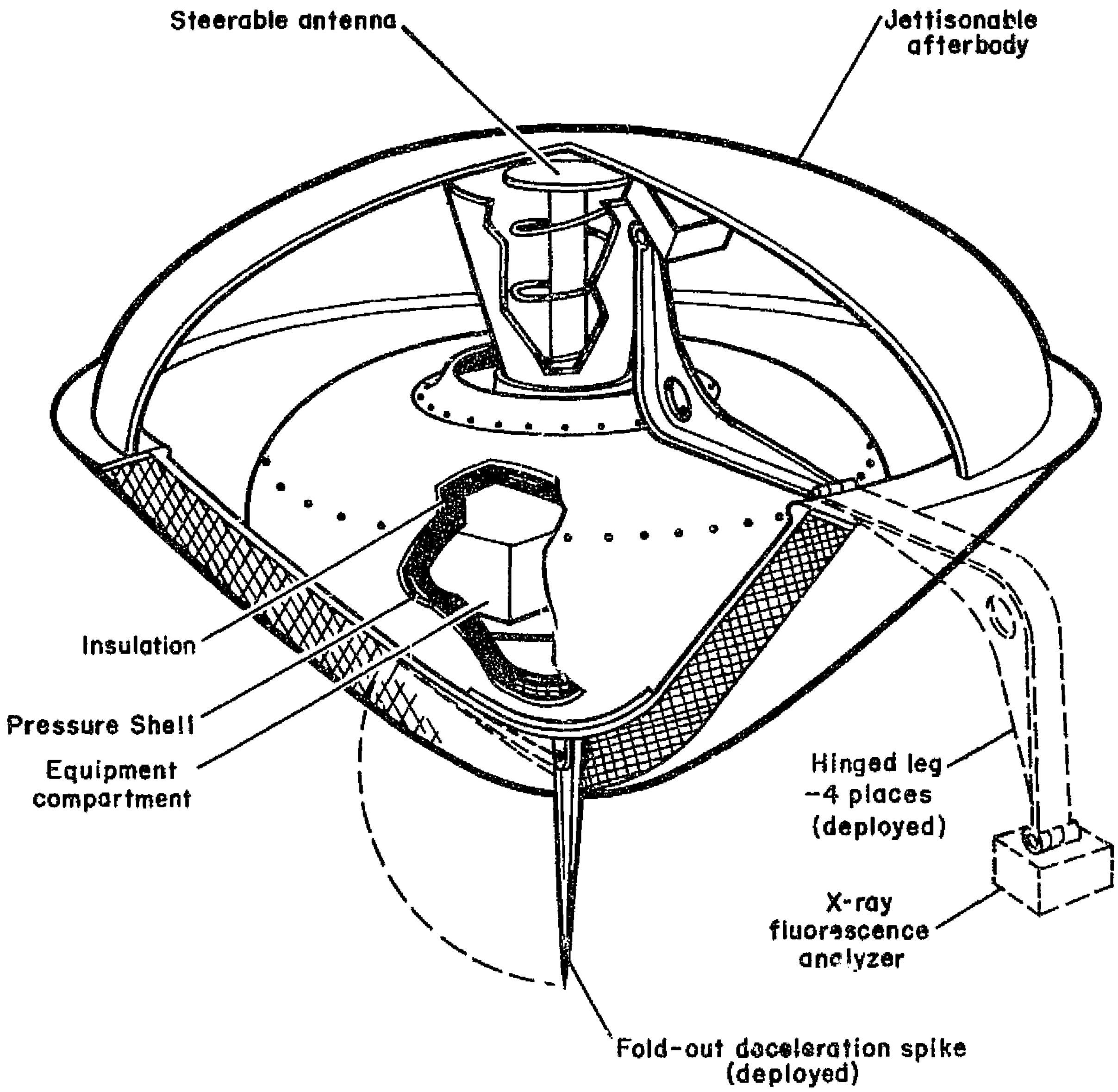

Figure 49.- Small geochemical lander.

It takes 5 min to acquire a x-ray sample and about 4 min to transmit these data to Earth. The x-ray instruments are operated in sequence, at least two and possibly three separate measurements can be acquired and transmitted to Earth for each of the four x-ray instruments.

9.4.3 Surface penetrators - Surface penetrators would be used to plant instruments below the surface and to couple them firmly to the Venusian soil. A number of mission options could be used to fly a penetrator mission; for the purpose of these discussions, the penetrators are assumed to be delivered from a flyby bus on direct entry trajectories. The penetrator jettisons its aeroshell soon after entry and drops through the atmosphere. Upon impact, it penetrates the surface and comes to rest at a depth of up to a few meters (depending on surface hardness). Communications is via a direct Earth link. A sketch of an implanted penetrator is shown in figure 50.

Penetrator missions at Venus suffer from the disadvantages of shallow penetration and from the requirements imposed by the high surface temperatures. The penetration depth depends on the impact speed and the hardness of the Venus surface layer. The impact velocity of a simple penetrator is the terminal speed (where atmospheric drag equals the penetrator weight) which is limited by the dense atmosphere to about 100 m/sec. Penetration depths are shown in figure 51 as a function of penetrator design and soil constant. The regolith material at Venus is expected to be granite or tuff. Note that even a heavy and dense penetrator achieves penetrations of less than 1 m in granite. A penetrator similar to the one proposed for Mars, for example, has a M/A = 0.49 kg/cm^2 and will penetrate 0.9 m below the surface at Venus. A rocket-assisted penetrator can be used to achieve higher impact speeds and deeper penetrations, but it will be considerably more complicated and expensive than a simple passive penetrator. The rocket-assisted penetrator was not considered in this study.

The design and operating life of the penetrator is dictated by the allowable operating temperature of the penetrator science instruments, electronics, and power supplies. If research on high-temperature electronics demonstrates a probability of developing this capability in the proper time frame, long-life penetrators could be developed where contained instruments are exposed to the thermal environment. Given this circumstance, penetrators present a viable mission option; based on current technology, however, where operating temperatures are limited, penetrators do not appear attractive for reasons given below.

Currently, the operating life of penetrators on Venus is limited by electronics, components that overheat and fail. A conventional penetrator would require insulation around its electronics to reduce the ambient heat input and internal phase-change material to absorb heat in order to achieve a significant operating lifetime. Designing conventional penetrators for long life presents inherent problems because of geometry constraints. The penetrator must be long and thin; a minimum fineness ratio (length of penetrator divided by diameter) of 10 is necessary to assure stability during penetration, but a fineness ratio greater than 20 should be avoided because of increased sidewall friction during penetration. Insulating the penetrator increases the diameter, which causes a corresponding increase in length because of the

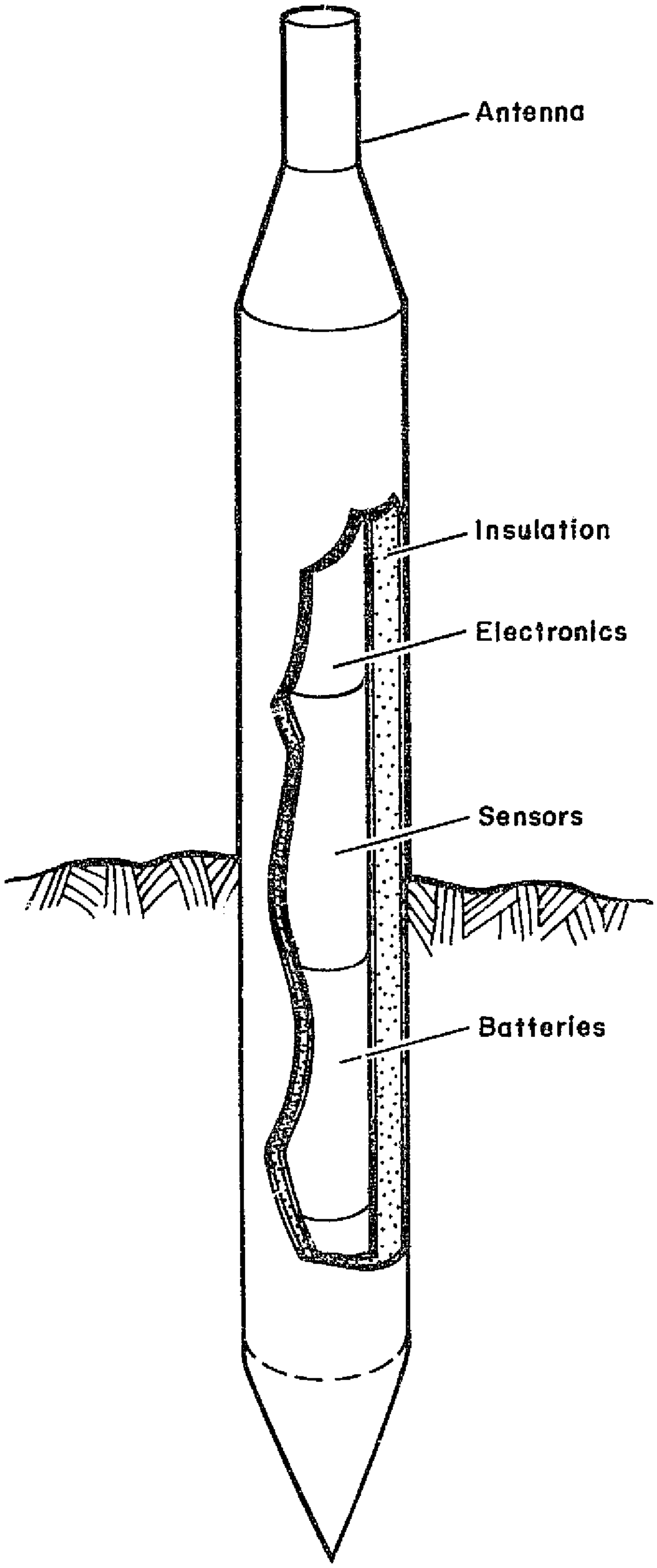

Figure 50.- Venus surface penetrator concept.

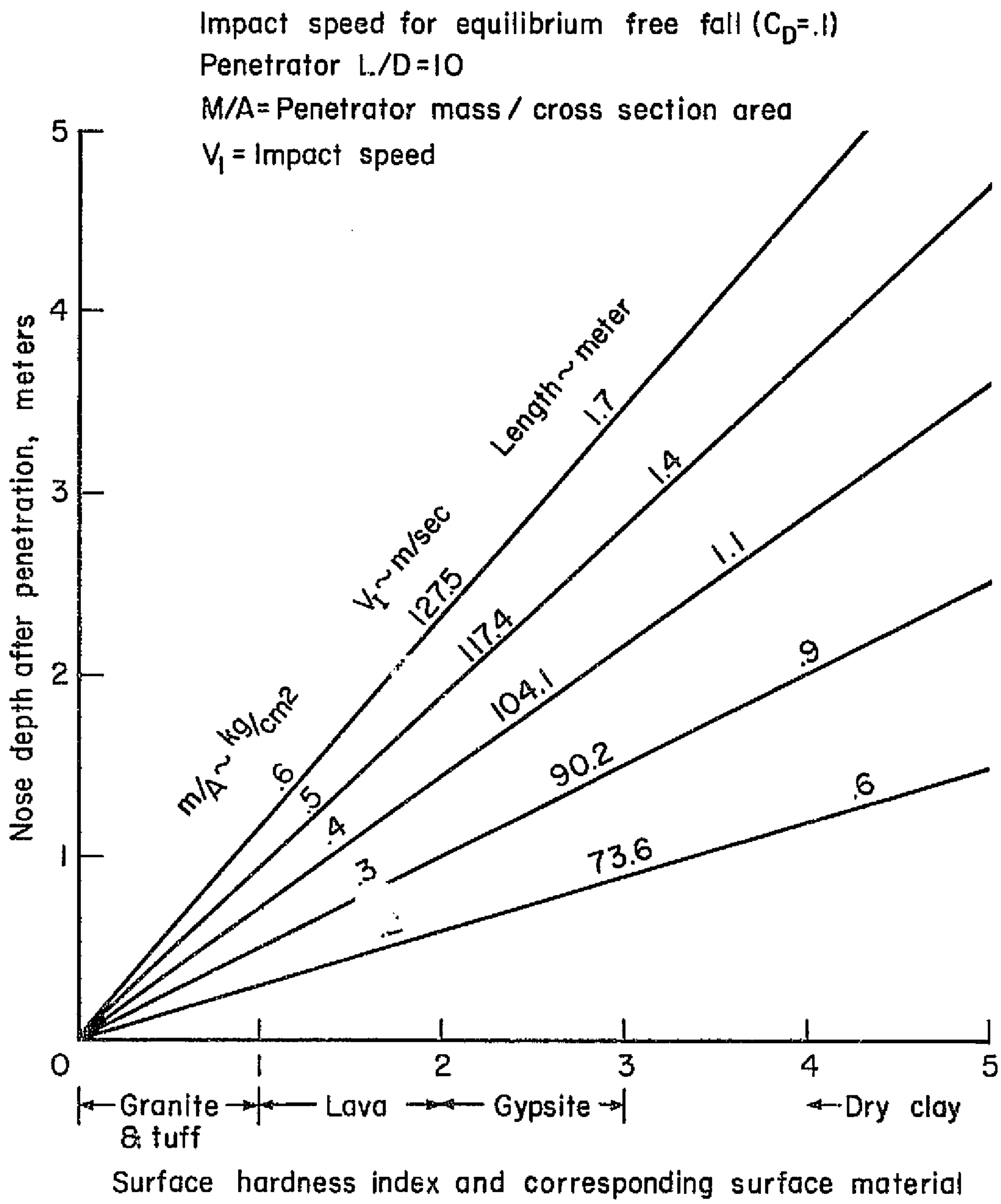

Figure 51.- Penetration depth.

fineness ratio constraint. Since the ratio of mass to frontal area must be kept large to assure adequate penetration, adding the lightweight insulation requires further design changes in the penetrator to add mass. The effect of these penetrator constraints is that a lifetime of only a few minutes can be achieved with modest amounts of insulation and phase-change material. Longer-life penetrators would be of such great length and mass that their feasibility is questionable. Thus penetrators are not presently an attractive option. As more information on Venus becomes available and when firm and science requirements are established, the question of penetrators should be re-examined.

9.4.4 Overall lander mission design - As described before, surface exploration of Venus could be accomplished by missions that deploy large landers, or by missions that deploy multiple small geochemical landers, or by missions involving combinations of both lander types. In this report, the combination mission option, which represents the most difficult mission, will be explored in more detail.

A representative combination mission could consist of one medium-lived large lander, three small geochemical landers, and the bus to deliver these landers to Venus. The overall launch configuration would be similar to the Pioneer-Venus multiprobe mission. The launch requirements for this lander mission are summarized as follows:

Large medium-lived landers.	545 kg
Small geochemical landers (3 @ 120 kg). .	360 kg
Bus spacecraft and midcourse fuel	300 kg
Total.	1205 kg
Contengency 10 percent.	120 kg
Spacecraft launch adapter	50 kg
Launch mass	1375 kg

The total system launch mass requirement of about 1375 kg can be readily met by either a Titan or Shuttle derivative in the mid-1980's. For example, the projected Shuttle/IUS is capable of launching from 3000 to 6000 kg for a Venus mission.

9.4.5 Technology requirements - The lander mission is projected for the time frame extending from the mid-1980's to the mid-1990's. Technology requirements for the lander mission are not well defined because of the "softness" of the mission and its dependence on the findings of precursor missions (including the Russian Veneras). The technology requirements for lander missions can differ radically, depending on lifetime requirements. Up to a lifetime on the order of hours, systems based on current technology may be used on the lander, but beyond this time, either active cooling or systems capable of operating at very high temperatures are required. Ultimately, for a true long-duration mission, systems (electronics, sensors, power supplies, etc.) are required that can operate at the maximum ambient surface temperature of Venus.

For short to moderate lifetimes, the key new technology requirements for the lander are the development of techniques to minimize the heat leaks through the insulation, and high-temperature mechanisms to operate the external moving parts of the lander such as sensors, optics, antennas, etc.

Studies are required to obtain a better definition of the lander system designs along with identification of the needed subsystem and science instrument technology developments. Studies are also required to determine an optimum design for the x-ray fluorescence instruments on the small landers.

9.5 Recommendations

At present, Venus is a geological unknown. Future exploration must include lander missions if exploration of Venus is to come to its logical conclusion. Direct measurements are a necessity, especially in view of the limited remote sensing capability. In any rational approach, however, lander missions must be preceded by a program of surface mapping so that landing sites can be selected prudently, thus ensuring that the measurements that are made are interpreted as unambiguously as possible. (Furthermore, results of early mapping may have a significant influence on the type of initial mission that is mounted or on the sequencing of initial and subsequent missions of different types.) Surface mapping of Venus requires the use of imaging radar systems. Advances have been made recently in Earth-based radar mapping and more are expected. An orbiting imaging-radar mission appears necessary, however, to obtain the resolution required to characterize the surface morphology adequately.

Following high-resolution radar mapping, surface landers must be used to make <u>in-situ</u> measurements of surface properties. The initial surface mission may use multiple probe landers, with up to 1-hr surface survival and limited measurement capability, a single capsule lander with 10 to 20 hr or more surface survival with multimeasurement capability, or a combination of the two. It is recommended that the combined mission be considered as the prime candidate until further studies are conducted that will determine which approach is most appropriate for the initial mission. Toward this end, the following work should receive early attention:

- Determine the feasibility of carrying out x-ray fluorescence analyses of surface materials on probe landers. The study should determine also to what extent similar analyses of cloud particulates could be performed during descent without compromising the surface analysis capability.

- Determine the time frames when radar imagery of large areas of the planet with 1 km and 200 m resolution will have been obtained and analyzed sufficiently to define the degree and extent of surface heterogeneity with the aim of determining whether or not some results will be obtained in times sufficiently early to influence the decision as to the most appropriate mission type.

- Examine the long-range goals of surface exploration of Venus and determine the most desirable and cost effective sequence of missions leading to that goal. One very important result of this study would be to identify sequential measurements that might be required to achieve the long-range goals. Specifically, the result should include an analysis of the immediate problem of whether probe landers, surface capsules, or combinations of the two would be most appropriate for the initial U. S. lander mission.

- Identify the role of shuttle in future missions to Venus.

Another study that should be performed, either parallel with or following the above, is to evaluate thoroughly the experiments that could be performed on probe and capsule landers and to refine mission plans. Problem areas should be identified that may require substantial research and development or that might impact the total scientific return. The following questions are examples of critical items that should be addressed:

(a) Can a window be designed for an insulated capsule that will produce a minimum heat short but that is also compatible with the optical systems of both the TV experiment and the spectral reflectance experiment?

(b) Are there problems in developing an imaging system, including the external motor-driven mirror mast and the illuminating devices that may pose developmental problems?

(c) Is the spectral reflectance approach valid in planetary exploration and, if so, can a preliminary design of such an instrument be considered?

(d) What is the feasibility of performing active seismic experiments on the surface and would such experiments be done best using a single-capsule lander or are multiple-capsule landers of unique design required?

(e) What are the most useful atmospheric measurements that could be made during descent and at the surface and what are the most appropriate experimental approaches?

It is clear that early funding of the above recommended studies is required. It is clear also that these studies will identify critical research and development that will be needed in the near future. They should also identify long lead-time research that will be required to develop future missions research such as that required to develop high-temperature electronics or unique refrigeration systems to ensure long surface lifetimes necessary for backside surveys and for more complex experiments. There is also need for research and development of sampling systems and advanced analytical instruments that would be used in future missions.

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APPENDIX A - PIONEER-VENUS PROGRAM

The Pioneer Venus program managed by the Ames Research Center encompasses two spacecraft missions, both planned to encounter Venus during the 1978 opportunity (fig. 52). The orbiter mission consists of an orbiter spacecraft, built by Hughes Aircraft Company, to be launched by an Atlas/Centaur from the CCAFS during a 10-day window in the period May 16-June 4, 1978, on a type-II transit trajectory to Venus. The spacecraft will encounter Venus and will be inserted into orbit on December 4, 1978, at 1800 GMT. The multiprobe mission consists of a bus spacecraft (with many design features in common with the orbiter spacecraft) carrying four atmospheric entry probes (one large and three identical small probes), built by a Hughes-General Electric Company team, to be launched by an Atlas/Centaur from the CCAFS during a 10-day window in the period August 5-26, 1978, on a type-I transit trajectory to Venus. The bus and entry probes, separated from the bus some 3 weeks prior to Venus encounter, will be separately targeted to arrive at Venus on December 9, 1978, some 5 days following orbiter insertion, within a maximum arrival time spread of 90 min, and subsequently make upper-atmospheric (bus) and lower-atmospheric (probes) measurements along predetermined descent trajectories which are widely separated spatially (in longitude and latitude) across the planet (fig. 5).

MULTIPROBE MISSION

The targeting capabilities at Venus of the five entry vehicles are quite flexible, and final selection of the target entry points will be made much later in the program. Current planning is summarized as follows:

Vehicle	Ecliptic[a] latitude-deg	Ecliptic[a] longitude-deg	Sun angle-deg	Comm. angle-deg	Relative[d] entry time
Bus	-52.0	60.0	56.5[b]	13.8[b]	E + 90 min
Large probe	0.0	71.0	71.0	52.3[c]	E + 0.0
Small probe 1	16.7	54.6	56.7	69.9[c]	E + 23.6 min
Small probe 2	17.7	179.3	153.4	58.3[c]	E + 18.4 min
Small probe 3	-50.7	104.8	100.2	50.0[c]	E + 4.0 min

[a]70-km altitude; subsolar point longitude = 0.0°; morning terminator longitude = 90°; antisolar point longitude = 180°.

[b]Slant entry at 180 km; communication angle between spin axis direction and direction to Earth.

[c]Vertical descent assumed; angle between vertical and direction to Earth.

[d]E at 200 km.

Three vehicles (bus, large probe, small probe 1) are targeted for dayside entry, and two vehicles (small probes 2 and 3) are targeted for nightside entry. The bus will make measurements only in the upper atmosphere above its

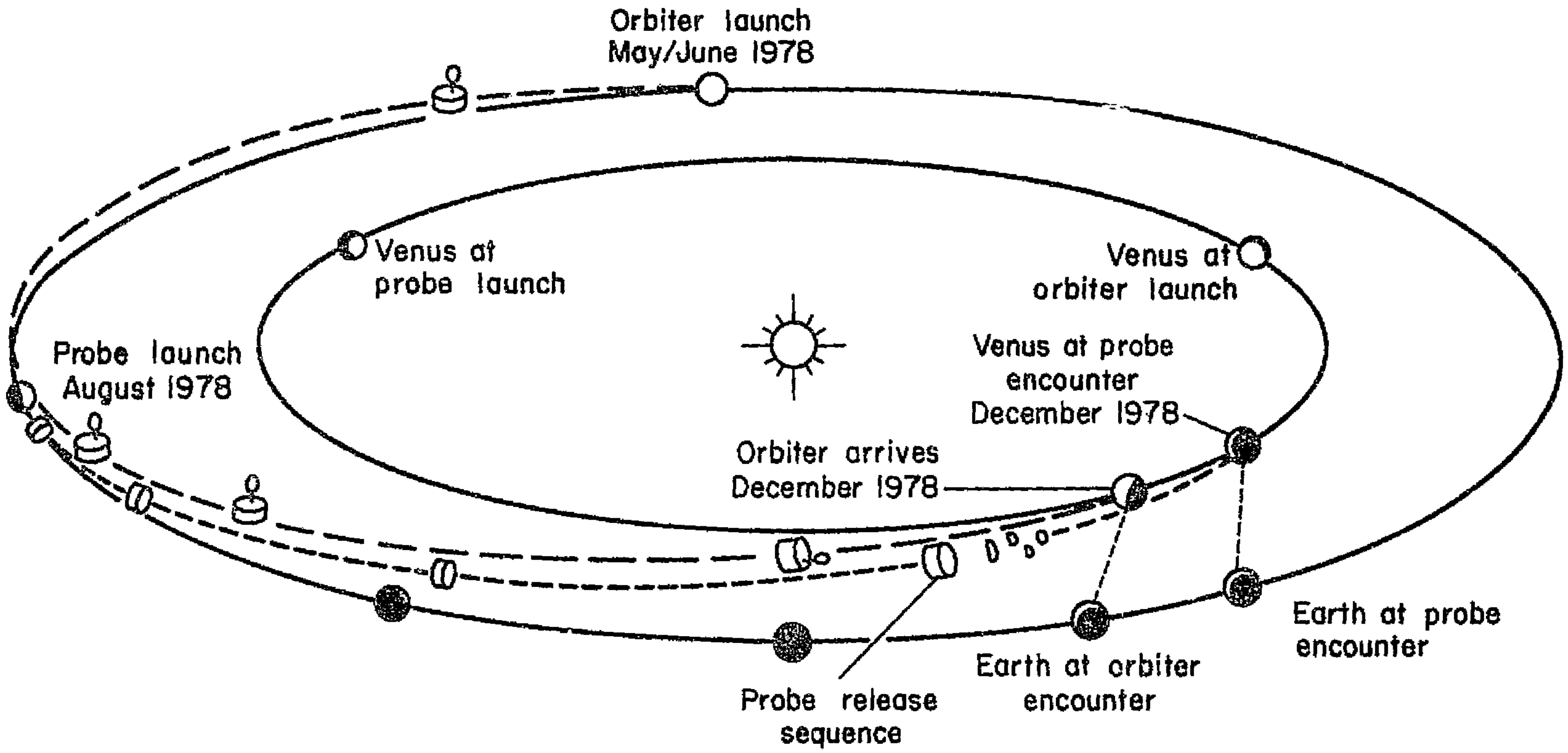

Figure 52.- Power Venus trajectories.

burn-up altitude of ~115 km, starting 4 hr before entry. It is targeted to a shallow (-10°) entry angle and for zero entry attack angle at 180 km to ensure adequate altitude resolution for its scientific instruments along its slant path at the high entry speeds (11.6 km/sec). No data storage is provided on the bus. Bus entry is retarded by 90 min relative to large probe entry primarily as a reference for the DVLBI experiment. Measurements will be made by the large and small probes from about 70-km altitude to impact. Survival on the surface is not planned nor expected. The particular targeting shown is chosen to maximize latitude and longitude dispersion within the geometric and communications restraints of the mission; in particular, small probe 1 is targeted for maximum daylight conditions (minimum solar zenith angle) with a resultant communications angle that does not permit a safety factor for reliable communications, hence scientific measurements, all the way to the surface. Also, the large probe, with its greater scientific accommodation capacity, is targeted for entry significantly in the daylight hemisphere (19° from the terminator) near the equator. Key time-sequence events for the probe entries are as follows:

Large probe:

Release from bus	E - 24 days (15 Nov. 1978)
Science warmup and calibration	E - 17 min (256 bits/sec real time)
Accelerometer on; configure for blackout	E - 5 min (128 bits/sec real time)
Entry (200-km altitude)	E + 0 (9 Dec. 1978)
RF blackout expected to begin	E + 12.7 sec (h ≅ 120 km)
Peak deceleration (322 g)	E + 19.5 sec
RF blackout expected to end	E + 20.5 sec (h = 76 km)
Parachute deploy (M ≤ 0.8)	E + 36.5 sec (h = 67.5 km)
Science on	E + 43.7 sec (h = 67.1 km)
Parachute jettison	E + 21.6 min (h = 44 km)
Impact	E + 59.1 min (h = 0)

Small probes:

Release (simultaneous) from bus	E - 20 days (19 Nov. 1978)
Science warmup and calibration	E - 17 min (64 bits/sec real time)
Accelerometer on; configure for blackout	E - 5 min
Entry (200-km altitude)	E + 0 (9 Dec. 1978)
RF blackout expected to begin	E + 20.5/6.8 sec (h ≅ 120 km)
Peak deceleration (193/576 g)	E + 32.0/10.9 sec
RF blackout expected to end; science boom deploy	E + 32.8/11.2 sec (h = 79/73.5 km); E + 45.4/17.6 sec (h = 72.0/66.0 km)
Change data rate (16 bits/sec real time)	E + 17.1/15.2 min (h = 30 km)
Impact	E + 60.8/59.6 min (h = 0)

As implied above, the small probes are permitted to enter and free fall to the surface, making measurements from about 70 km to the surface in a time period of ~60 min. (The slashed figures encompass the extremes appropriate

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to the three small probes.) The large probe, however, is suspended from a parachute with a 12.2-ft diameter to retard its descent rate for about 20 min from about 67 km to 44 km; it will then fall freely below 44 km. The total descent time is again estimated to be about 59 min. The accelerometer is the only instrument that will be operative above 70 km on all probes; its data will be stored throughout blackout at 74 bits/sec on the large probe and at 36 bits/sec on the small probes in a 3072-bit memory. The data will also be transmitted to Earth in real time.

The bus and probes have been designed and sized to accommodate the scientific requirements of the experiments chosen for the multiprobe mission. These requirements are summarized as follows:

Vehicle	Number of experiments	Weight, lb	Volume, cu. in.	Power, W	Data rate, bits/sec	Pressure vessel ID, in.
Bus	2	25	1000	30	8-2048	---
Large probe	7	75	3446	106	256,128[b]	28.8
Small probes[a]	3	8	175	10	64/16[c]	18.0

[a]Each small probe carries identical experiments; numbers shown are for each small probe.

[b]Storage only.

[c]Change at 30 km.

The (nonradio) scientific experiments, principal investigators, and their current requirements for mass, volume, and average power are shown below.

Experiment	Principal investigator	Mass, lb	Volume, cu. in.	Power, W
Large probe:				
Atmosphere structure	A. Seiff/ARC	5.15	90	4.9
Nephelometer	J. Blamont/CNES; B. Ragent/ARC	1.9	60	2.0
Cloud particle size spectrometer	R. G. Knollenberg/PMS	8.5	260	20.0
Infrared radiometer	R. W. Boese/ARC	5.5	102	4.0
Neutral mass spectrometer	J. H. Hoffman/UTD	22.5	660	12.0
Gas chromatograph	V. I. Oyama/ARC	12.5	526	40.0
Solar flux radiometer	M. G. Tomasko/Ariz.	4.0	100	4.0
TOTAL		60.05	1798	86.9
Small probe:				
Atmosphere structure	A. Seiff/ARC	2.43	70	3.6
Nephelometer	J. Blamont/CNES; B. Ragent/ARC	1.9	60	2.0
Net flux radiometer	V. E. Suomi/Wisc.	2.03	32	2.5
TOTAL		6.36	162	8.1

Experiment	Principal investigator	Mass, lb	Volume, cu. in.	Power, W
Bus:				
Neutral particle mass spectrometer	U. Von Zahn/Bonn	15.0	580	5.0
Charged particle mass spectrometer	H. A. Taylor/GSFC	5.1	174	1.5
TOTAL		20.1	754	6.5

In addition to the above, a set of radio science experiments will be performed using all entry vehicles and their associated S-band telemetry systems. Each entry vehicle transmits directly to Earth; transponder links are provided on the bus and large probe, whereas stable oscillators are on each small probe.

In addition to those scientists listed above, the Pioneer Venus multiprobe mission science steering group consists of several interdisciplinary scientists: R. Goody/Harvard, T. Donahue/Michagin, D. Hunten/KPNO, J. Pollack/ARC, S. Bauer/GSFC, and N. Spencer/GSFC.

ORBITER MISSION

The key elements of the currently planned Pioneer Venus orbit and spacecraft characteristics are given below:

Orbit:	
Periapsis altitude	200 km nominal[a]
Apoapsis altitude	66,200 km
Orbital period	24 hr[b]
Orbital inclination	105° (retrograde)
Periapsis latitude	15.8-32.1° North[c]
Mission lifetime	≥243 days on-orbit[d]
Spacecraft:	
Stabilization	Spin-stabilized; spin-axis perpendicular to ecliptic[e]
Spin-rate	5 rpm (on-orbit); 15 rpm (cruise)

[a]7-8 apoapsis trim maneuvers during nominal mission lifetime to maintain periapsis altitude in the range 150-260 km.

[b]8 periapsis trim maneuvers during the nominal mission lifetime to maintain the 24-hr period to ±10 min.

[c]Actual periapsis latitude depends on launch date: 15.8°N and 32.1°N appropriate to May 24 and June 4 launches, respectively.

[d]One Venus day; to be extended if feasible.

[e]Positive spin-axis aligned with south ecliptic pole on-orbit; positive spin-axis aligned with north ecliptic pole during cruise.

Twelve (nonradio) scientific experiments are included in the orbiter payload. The experiments, principal investigators, and their current requirements for mass, volume, shelf footprint, and average power are shown below. The onboard data-handling system has a storage memory with a capacity of 1.048×10^6 bits of data.

Eleven play-back and real-time data-transmission rates between 8 and 2048 bits/sec are available on-orbit; a transmission rate of 1024 bits/sec is used during cruise.

In addition to the above, five radio-science experiments will be performed using the S-band telemetry system and an X-band beacon specially provided for this purpose. The latter consists of a 750-mW transmitter, phase-coherent (11/3) with the S-band system. Its primary use is for the dual-frequency radio-occultation experiment. Both signals are transmitted to the NASA DSN 64-m net through the spacecraft high-gain, 43-in.-diameter, mechanically despun telemetry antenna. Elevation steering is provided for up to 15° refraction tracking. Key periods during the mission are also shown below.

Experiment	Principal investigator	Weight, lb	Volume, cu. in.	Footprint, sq. in.	Power, W
Neutral particle mass spectrometer	H. B. O. Niemann GSFC	8.4	92	59	9.0
Charged-particle mass spectrometer	H. A. Taylor, Jr. GSFC	5.1	165	25	1.5
Electron temperature probe	L. H. Brace GSFC	4.4	154	33	2.0
Retarding potential analyzer	W. C. Knudsen LMSC	6.0	157	23	2.8
Ultraviolet spectrometer	A. I. Stewart LASP	6.9	341	40	0.9
Infrared radiometer	F. W. Taylor JPL	12.3	625	90	2.5
Cloud photo-polarimeter	J. E. Hansen GISS	9.0	300	70	6.4
Magnetometer[a]	C. T. Russell UCLA	4.2	192	32	3.0
Plasma analyzer[a]	J. H. Wolfe ARC	7.5	483	44	3.0
Electric field detector[a]	F. L. Scarf TRW	1.2	33	18	0.6
Surface radar mapper	b	24.0	520	80	30.0
Gamma burst detector[a]	W. D. Evans LASL	5.3	110	26	2.0
TOTAL		94.2	3172	540	63.7

[a]Also used in cruise mode.

[b]No principal investigator named. Radar mapper team composed of G. H. Pettengill/MIT, D. H. Staelin/MIT, W. E. Brown, JPL, W. H. Kaula/UCLA, H. Masursky/USGS, and G. McGill, Mass.

Encounter (Dec. 4, 1978)	E + 0
Occultations (22 min max)	E + 0 to E + 74 days
Eclipses (23 min max)	E + 27 to E + 120 days
Occultations (3.16 hr max)	E + 156 to E + 165 days
Eclipses (3.23 hr max)	E + 183 to E + 189 days
End of mission (Aug. 4, 1979)	E + 243 days

In addition to those scientists mentioned above, the Pioneer Venus Orbiter Mission Science Steering Group consists of several interdisciplinary scientists: T. M. Donahue/Mich., A. F. Nagy/Mich., G. Schubert/UCLA, H. Masursky, USGS, and G. E. McGill/Mass. (The last two scientists are also members of the Surface Radar Mapper team.)

APPENDIX B - MISSION ANALYSIS AND LAUNCH VEHICLES

MISSION OPPORTUNITIES

Opportunities to launch missions to Venus occur five times each 8 years, when the Earth-Venus geometry is favorable. The geometry and hence the mission opportunities repeat almost exactly each 8 years.

At each mission opportunity, two different types of trajectories may be used from Earth to Venus. The shorter, called type-I trajectories, take about 120 days to reach Venus. The longer, called type-II trajectories, take about 160 days to reach Venus. Each trajectory type usually involves different launch-energy requirements and Venus approach velocities, so the best one must be determined for each type of mission.

DIRECT ENTRY MISSIONS

Direct entry missions (such as atmosphere probes, balloons, or landers) can be flown on either type-I or type-II trajectories. The choice of which to use generally depends on the amount of mass that can be lifted by the launch vehicle and the communication distance from Venus to Earth. The Venus approach velocity is only a secondary consideration because heat-shield mass does not change greatly for the range of approach velocities that will be encountered.

Some of the trajectory parameters for typical direct-entry missions are summarized in table XXXIV. Note that type-I trajectories lead to shorter communication distances and probably will be used for missions that require communication directly from the vehicle to Earth.

ORBITER MISSIONS

Orbiter missions can be flown on either type-I or type-II trajectories. The choice of which to use involves a complicated balancing of launch mass and fuel used for orbit insertion to maximize the net mass in Venus orbit. Since orbiters generally operate in orbit for many months, the communication distance from orbiter to Earth will always include the maximum range, so the communication system will be the same for type-I and type-II trajectories. Some of the trajectory parameters for typical orbiter missions are shown in table XXXV. For some launch years, only one trajectory type is shown because the other type is too unfavorable.

One of the most important items for orbiter missions is delivered mass in Venus orbit. The difference between launch mass and delivered mass in Venus orbit is the mass of the orbit insertion propulsion system which, in turn, is highly dependent on the required Venus orbits and propulsion system performance. For a given launch weight, the approximate net in-orbit mass can be found from

TABLE XXXIV.- DIRECT-ENTRY MISSION CHARACTERISTICS

Launch year trajectory type	Earth launch date	Venus arrival date	Earth escape energy (10-day launch period), km^2/sec^2	Spacecraft launch mass, Atlas/Centaur, kg	Venus-Earth communication distance at arrival, km
1980					
I	March 1980	June 1980	12.34	719	60×10^6
II	April 1980	Sept. 1980	8.6	835	139×10^6
1981					
I	Nov. 1981	Feb. 1982	13.61	685	60×10^6
II	Nov. 1981	April 1982	7.6	869	116×10^6
1983					
I	June 1983	Oct. 1983	8.38	844	93×10^6
II	May 1983	Oct. 1983	6.1	919	93×10^6
1985					
I	Jan. 1985	May 1985	7.7	866	70×10^6
II	Nov. 1984	May 1985	13.5	687	70×10^6
1986					
I	Aug. 1986	Dec. 1986	8.45	846	59×10^6
II	Sept. 1986	March 1987	10.9	762	146×10^6
1988	Same as 1980				
1989	Same as 1981				
1991	Same as 1983				

TABLE XXXV.- ORBITER MISSION CHARACTERISTICS

Launch year trajectory type	Earth launch date	Venus arrival date	Earth escape energy (10-day launch period), km^2/sec^2	Spacecraft launch mass, Atlas/Centaur, kg	Venus approach velocity, km/sec
1980					
I	April 1980	July 1980	18.2	561	4.7
II	Significantly lower mass in orbit				
1981					
I	Nov. 1981	March 1982	16.9	594	3.6
II	Significantly lower mass in orbit				
1983					
I	June 1983	Oct. 1983	11.0	760	3.1
II	May 1983	Nov. 1983	6.4	910	3.6
1984					
I	Dec. 1984	May 1985	12.9	706	4.0
II	Nov. 1984	May 1985	14.7	653	3.1
1986					
I	Aug. 1986	Dec. 1986	10.7	769	4.9
II	May 1986	Dec. 1986	19.6	522	3.4
1988	Same as 1980				
1989	Same as 1981				
1991	Same as 1983				

figure 53 for different orbit eccentricities and for a choice of propulsion system types.

LAUNCH VEHICLES

A variety of launch vehicles can be considered for missions that follow Pioneer Venus. In addition to the expendable launch vehicles now in use, reusable vehicles incorporating a space shuttle will be available in the mid-1980's. The choice of a launch vehicle for any particular mission is usually made to minimize the overall cost of the mission. The result is usually to select the smallest launch vehicle that will allow a scientifically important mission to be performed. However, depending on the availability of the expendable launch vehicles and launch scenarios for the 1980's, all Venus missions may be flown on the shuttle. Such scenarios could have a significant impact on spacecraft design and mission cost by negating differences in launch costs for most Venus missions.

The weight-lifting capability of several typical candidate launch vehicles is shown in figure 54. Since the missions described in the text generally have launch masses in this range of 800-4000 kg, there will be a reasonable selection of vehicles available over the entire timeframe of interest. Depending on the choice of the upper stage for the shuttle, the shuttle/IUS can launch from 3000-4000 kg to Venus.

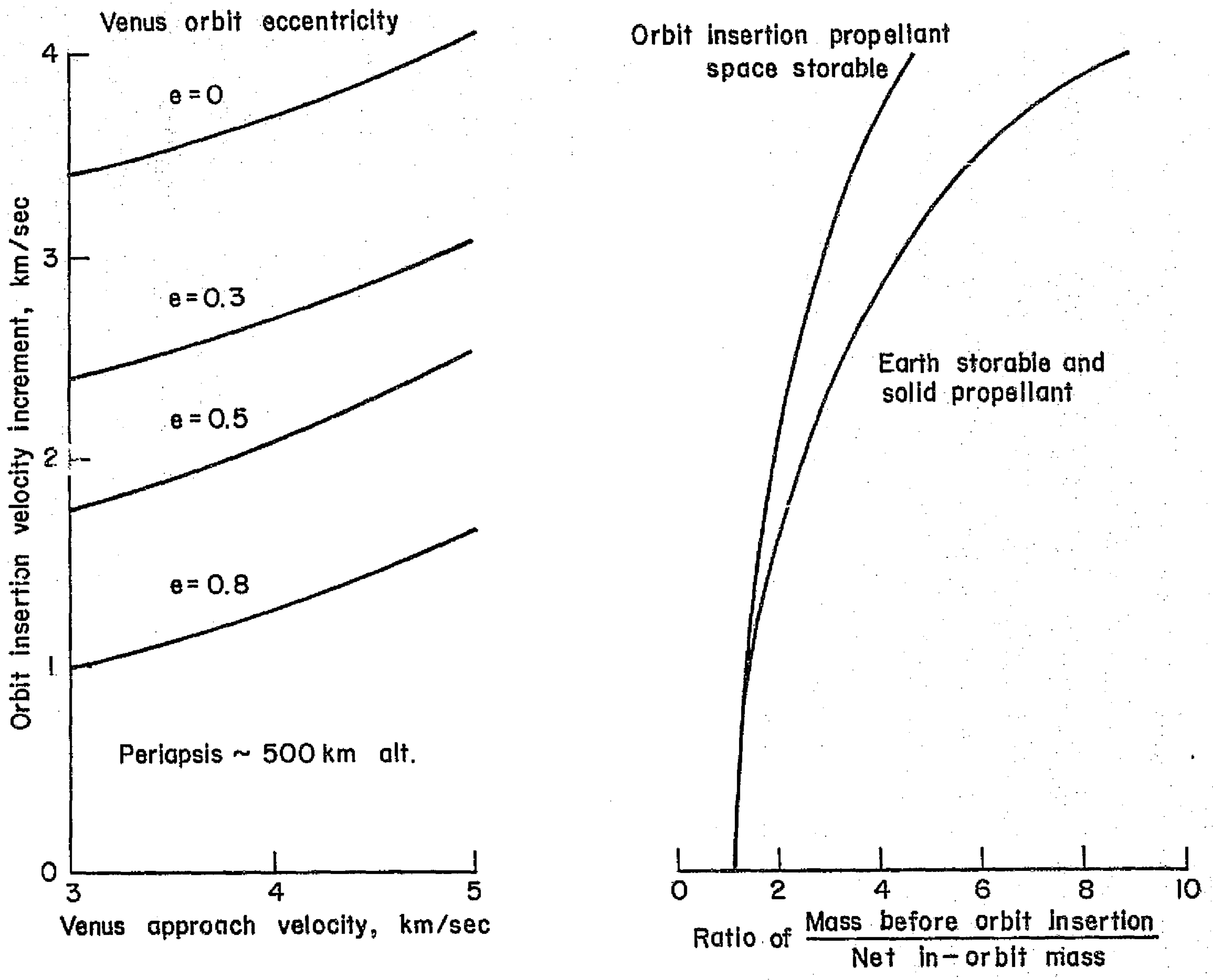

Figure 53.- Venus orbiter net in-orbit mass.

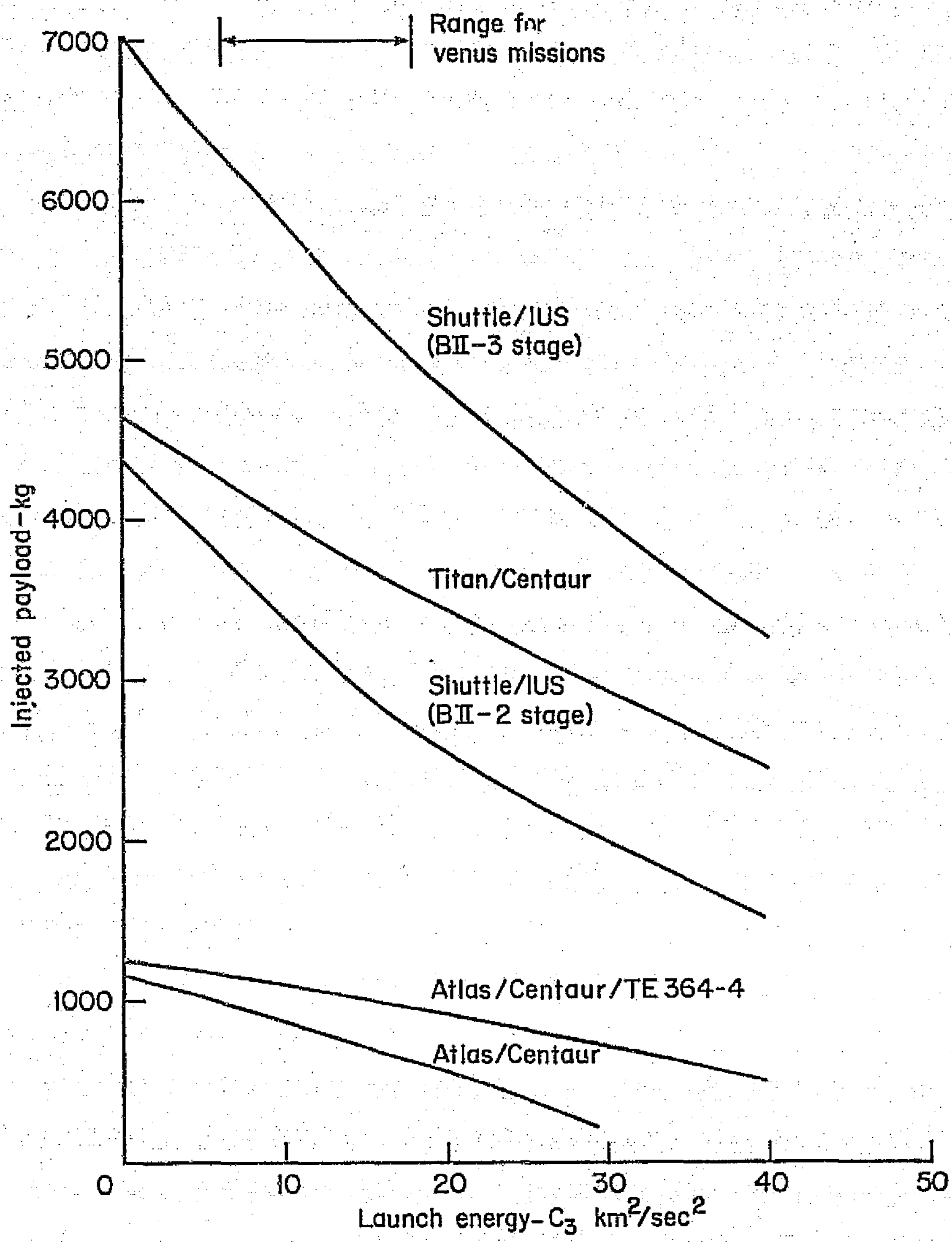

Figure 54.- Launch vehicle performance.

APPENDIX C - USE OF CRATERING DATA FOR ANALYSIS OF VENUS GEOLOGIC HISTORY

The study of crater morphology, the frequency of craters, the form of the crater frequency distribution function, and the gross spacial distribution of craters has been a primary means of the remote determination of the gross geologic history of a planet or its moon. While there are large uncertainties in the absolute ages of the surfaces derived from the study of crater statistics, it is apparent that this data base has provided most of our information regarding the nature and history of geologic processes acting on the surfaces of the Moon, Mars, Mercury, Phobos, and Deimos. It is possible to review recent work of this type for the study of Mars to show what can be done and how this type of analysis might be used in studies of the geology of Venus. If crater studies are judged to be of value, such a judgment would support a Venus orbiting imaging radar mission.

The first use of crater distributions involves the total frequency distribution. For example, the lunar highlands are densely cratered, and the maria are sparsely cratered. It is now known, based on the lunar sample dates, that the heavy period of bombardment of the Moon was in the first billion years of its history. There is on Mars a spatial dichotomy in crater density similar to the dichotomy between the heavily cratered lunar highlands and the sparsely cratered lunar maria. Since the lunar maria are as old as 3.65 billion years and are sparsely cratered, the dichotomy on Mars suggest that some parts of Mars are very ancient and were present during the period of heavy bombardment, and the sparsely cratered areas may be of a variety of recent ages that reflect the lower levels of cratering. The most heavily cratered terrains of the Moon and Mars reflect an early period of cratering. Soderblom (ref. 94) has argued that since the oldest postaccretional mare-like surfaces on Mars and the Moon display the same crater density, then the impact fluxes at Mars and the Moon have been about the same over the last 4.6 billion years. He has used the observed density of craters between 4 and 10 km, formed after the early rapid period of crater formation, to determine the sequence of emplacement of cratered plains, volcanic ridge complexes, and fractured plains. If cratering rates on the Moon and Mars are equal, then there is the hope that some meaningful interplanetary correlations of geologic events may be possible.

Changes in the slope of the total frequency distribution have also provided evidence of an obliteration process on Mars that appears not to have operated on the lunar surface. Martian craters appear to be much more subdued than lunar craters. The crater morphology alone suggests that the surface processes acting over a long period of time have been different on Mars than on the Moon. Craters larger than about 30 km are characterized by the relationship $N = KD^{\alpha}$, where N is the number of craters of diameter D, K is a constant, and $\alpha = -3$. Craters smaller than 30 km correspond to a more positive value of α than -3. Öpik (ref. 157) was the first to infer from the existence of the change in slope that some craters had been obliterated as cratering proceeded. It has recently been shown (refs. 158-161) that changes in the slope of crater frequency distributions can be produced as a result of a number of obliterative processes acting as the craters are produced. Aeolian, fluvial, and certain types of volcanic processes can produce the observed

changes in the distributions. Crater distributions of this type have been produced experimentally by deposition of material as the craters form, and similar results are generated in computer models using constant obliteration rates or obliteration intervals followed by more intense periods of obliteration.

Therefore, the observed Martian crater frequency distributions suggest at least one period of obliteration, and some investigators believe that a second period of increased obliteration is required to explain the data (refs. 158, 160, and 161). For example, Chapman (ref. 160) duplicated the total frequency distribution of Martian craters using computer models that assumed that, during the first 93-percent of Martian cratering history, obliteration proceeded at a relatively low level. Then the obliteration increased relative to cratering by a factor of 20 for the next 2.3 percent of cratering history. During the last 4.7 percent of cratering history, the obliteration rate decreased markedly. The major uncertainty is in the absolute time scale that should be assigned to each period of activity. Chapman (ref. 160) converts his relative values to absolute time scales for three different values of the ratio of Martian cratering rates to lunar cratering rates. When the ratio is 1, the second obliteration period is merely a slackening in the rate of obliteration rather than the abrupt increase that took place between 3 and 4 billion years ago. The overall pattern resembles that hypothesized by Soderblom (ref. 94), who ties the obliteration history to the early period of cratering. When the ratio is 5, the period of obliteration is indicated to have occurred between 1 and 2 billion years ago (see ref. 158). When the ratio is 25, as assumed by Jones (ref. 161), a pronounced period of obliteration is indicated 450 million years ago. Jones notes that the crater densities on some of the old cratered plains and on the heavily cratered terrain are equal, and there are only a few degraded craters on the plains; therefore, the plains were emplaced toward the end of the second period of obliteration. Jones described channels on the plains units and suggested that they might be evidence that a fluvial process obliterated some craters. Jones relies heavily on maxima in the frequency distributions of degraded craters. According to his results, the distribution of all craters is a less sensitive indicator of a past obliteration event because fresh craters formed after the obliteration event obscure the diagnostic maxima in the frequency distribution of degraded craters.

While his frequency distributions do exhibit slight decreases in crater frequency just above 10 km, it is not possible to demonstrate a decrease in crater frequency below 10 km because all craters smaller than 10 km were classified as fresh due to resolution constraints (ref. 161). Therefore, due to resolution limitations in the data, it will probably not be possible for large continuous areas to confirm the detailed changes in the predicted frequency of craters smaller than 10 km that would be produced by a second period of obliteration. Nevertheless, the analysis of crater distributions provide a great amount of information about surface processes and about the geologic history of planetary surfaces. While Hartmann (ref. 158), Chapman (ref. 160), and Jones (ref. 161) argue for episodes of obliteration, Soderblom (ref. 94) argues that cratering rates have been similar on Mars and the Moon. This yields the result that the period of major obliteration was contemporaneous with the early intense period of cratering. Arvidson (ref. 162) used results of classification of crater shape to show, assuming similar cratering

rates, that the fresh craters have been retained for 3.3 billion years. Therefore, the major period of obliteration occurred prior to 3.3 billion years ago if the cratering rates on Mars are equal to those on the Moon. Note that Soderblom has documented very recent mantling of craters 0.6 km to 1.5 km in diameter at latitudes north and south of +40° and -40° latitudes. He related this to changing patterns in the atmospheric circulation in recent history.

Our present ideas about the geologic history of Mars, starting with an early heavy bombardment coupled with other obliterative processes and followed by a less intense period of cratering during which tectonic features, volcanoes, and plains units were emplaced and during which a second episode of obliteration has possibly taken place, are all based on analysis of crater statistics. Data required to make these findings consist of total crater frequency data, spatial variations in crater density, and the morphology of craters. It is emphasized that part of the present uncertainty in the degree of importance of a second period of obliteration results from the lack of the resolution over large areas of the same part of Mars required to classify the shape of craters less than 10 km in diameter.

APPLICATION OF CRATER STATISTICS TO VENUS STUDIES

There is reason to believe from considerations of the study of the thermal history of Venus that differentiation has taken place, that volcanic features may be present, and that water may have been present on the surface in the past. The possibility exists that aeolian or fluvial sedimentation, volcanism, igneous activity, and plate tectonics may have been important Venusian processes. While large impact craters are rare features on Earth, limited radar data for Venus (ref. 86) have already revealed the presence of a number of craters and some very large circular structures ("alpha") that may be craters. Some of the Venusian surfaces may be very ancient, and large areas of ancient heavily cratered terrain are possible. Important features of planetary evolution have been deduced from the existence of large tracts of heavily cratered terrain on Mercury. Murray et al. (ref. 69) have concluded that differentiation occurred very early in the history of Mercury from the fact that large areas of high populations of large craters could not survive the global effects of differentiation if it took place after most of the craters were formed. The number and spatial distribution of Venusian craters may provide the same basic type of information. For example, the Venusian surface may exhibit the same dichotomy in distribution of its heavily and sparsely cratered terrain. If so, similarities on the Moon, Mars, Mercury, and Venus may begin to place constraints on planetary evolution.

A comparison of the frequency of craters with lunar frequencies will provide a first estimate of the age of the cratered surface, but this will be subject to the same uncertainties in relative cratering rates for Venus and for the Moon as for Mars and the Moon. Such uncertainties, however, may be clarified if the oldest post-accretional surfaces on Venus also have the same crater distributions as the oldest post-accretional lunar surfaces.

If Venus is an active planet and surface processes have in the past or now consist of aeolian, fluvial, volcanic, or isostatic processes, the existence of such processes and some information regarding the history of such processes may be deduced from study of the morphology and frequency distributions of craters in the same way as for Martian history. If the Venusian crater distributions exhibit marked changes in slope, their frequency distribution should be modeled by combining cratering with obliterative processes. Volcanism, fluvial erosion, and aeolian erosion all can account for the type of crater frequency distribution on Mars. Perhaps these types of processes will also satisfactorily duplicate Venusian crater frequency distributions. Changes in the slope of crater frequency distributions, if present, may extend to larger diameters, which might be taken as evidence of higher relative surface activity. Such results may help to place Venus in the sequence of planetary activity.

The very large craters on Mars are degraded, and Chapman (ref. 160) has argued that this might reflect isostatic compensation of very large cratered floors. This may be even more common for large Venusian craters. The possibility even exists that, if aeolian, fluvial, and volcanic processes have not been effective in obliterating small craters, than only the large craters may have been obliterated due to isostatic effects. If so, a different type of obliteration history may be reflected in the crater frequency distributions. It is certain that crater statistics will provide important clues to the geologic history of Venus. It is important that small craters be resolved in enough detail that their morphology can be determined. We have already shown how improved resolution of craters less than 10 km in diameter could have provided a critical test of a second period of obliteration of Martian craters. The relative frequency of craters 0.6 to 1.2 km in diameter have been used to map the mantled terrain on Mars, and mantling has been related to important characteristics of atmospheric circulations patterns.

It may reasonably be expected that the statistics of small craters also will be important in studies of Venusian geologic history. While it is difficult to state exactly how they may be used, it is certain that their distribution and morphology will be important. Perhaps their distribution may be used to describe mantling resulting from aeolian effects, as they were used on Mars. Or perhaps they may be used to show basic differences in surface processes. For example, the 100-bar pressure at the base of the Venusian atmosphere may prohibit formation of primary craters smaller than about 1 km. In that event, any orbiter mission should have the capability of resolving craters smaller than 1 km in diameter because any impact craters detected in this size range would be secondary craters. This means that, since large areas of surface formations less than about 3.5 billion years old on the Moon only rarel contain craters larger than 1 km, most areas sampled on such surfaces on Venus may also lack craters in this size range. Since craters this size are responsible for producing most of the lunar mare regolith, their absence on Venus would indicate the absence of an impact-generated regolith. Therefore, the possibility exists that the geologic units 3-3.5 billion years old and younger on Venus will either contain a regolith generated only by secondary craters or one generated by other nonimpact types of surface processes.

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REFERENCES

1. Moore, P. M.: The Planet Venus. MacMillan Co., 1959.

2. Abell, G.: Exploration of the Universe. Holt, Reinhart, and Winston Co., 1969.

3. Koenig, L. R.; Murray, F. W.; Michaux, C. M.; and Hyatt, H. A.: Handbook of the Physical Properties of the Planet Venus. NASA SP-3029, 1967.

4. Bronshten, V. A.: The Planet Venus. NASA TT F-14,519, Dec. 1972.

5. Kuzmin, A. D.; and Marov, M. Ya.: Physics of the Planet Venus. NASA TT F-16,226, June 1975.

6. Lewis, J. S.: The Atmosphere, Surface and Clouds of Venus. American Scientist, vol. 59, Sept./Oct. 1971, pp. 557-566.

7. Anon.: Venus-Strategy for Exploration. National Academy of Sciences, Report of a Study by the Space Science Board, June 1970.

8. Marov, M. Ya.: Venus: A Perspective at the Beginning of Planetary Exploration. Icarus, vol. 16, 1972, pp. 415-461.

9. Anon.: Pioneer Venus, Report of a Study by the Science Steering Group. Ames Research Center, June 1972.

10. Lewis, J. S.; and Friedman, L. D.: Future Exploration of Venus. Astron. and Aero., vol. 13, May 1975, pp. 46-58.

11. Goody, R. M.; and Donahue, T. M.: Presentation to the House Committee on Science and Astronautics, March 15, 1973.

12. Goody, R. M.; and Walker, J. C. G.: Atmospheres. Prentice-Hall, Inc., Foundations of Earth Science Series, 1972.

13. Anon.: Mariner-Venus 1962, Final Project Report. NASA SP-59, 1965.

14. Vakhnin, V. M.: A Review of the Venera 4 Flight and Its Scientific Program. J. Atmos. Sci., vol. 25, 1968, pp. 533.

15. Anon.: Mariner-Venus 1967, Final Project Report. NASA SP-140, 1971.

16. Sheldon, C. S.: Soviet Space Programs, 1966-1970. Doc. 92-51, Lib. of Cong. Staff Rep., Washington, D. C., Dec. 9, 1971.

17. Marov, M. Ya.: Venus. NASA TT F-16,210, April 1975.

18. Anon.: Science. Special Issue on Mariner 10 Results, March 29, 1974.

19. Anon.: Pioneer Venus Orbiter Mission Experiments Description. PD-401, Ames Research Center, Jan. 1975.

20. Anon.: Pioneer Venus Multiprobe Mission Experiments Description. PD-402, Ames Research Center, Jan. 1975.

21. Ainsworth, J. E.; and Herman, J. R.: Venus Wind and Temperature Structure: The Venera 8 Data. J. Geophys. Res., vol. 80, Jan. 1, 1975, pp. 173-179.

22. Anon.: Pioneer Venus, "Pioneer Venus Orbiter Report of a Study by the NASA/ESRO Joint Working Group," Ames Research Center, Jan. 1973.

23. Anon.: Opportunities and Choice in Space Science, 1974. National Academy of Sciences, 1975.

24. Kavanagh, L. D., Jr.; Schardt, A. W.; and Roelof, E. C.: Solar Wind and Solar Energetic Particles: Properties and Interactions. Rev. Geophys. and Space Phys., vol. 8, 1970, p. 389.

25. Dolginov, Sh. Sh.; Yeroshenko, Ye. G.; and Lewis, L.: Nature of the Magnetic Field in the Vicinity of Venus. Cosmic Res., vol. 78, 1973, p. 4779.

26. Ness, N. F.; Behannon, K. W.; Lepping, R. P.; Whang, Y. C.; and Schatten, K. H.: Magnetic Field Observations Near Venus: Preliminary Results From Mariner 10. Science, vol. 183, March 29, 1974, p. 1301.

27. Fjeldbo, G.; and Eshleman, V. R.: Atmosphere of Venus as Studied With the Mariner-5 Dual Radio Frequency Occultation Experiment. Radio Science, vol. 4, 1969, p. 879.

28. Howard, H. T.; Tyler, G. L.; Fjeldbo, G.; Kliore, A. J.; Levy, G. S.; Brunn, D. L.; Dickenson, R.; Edelson, R. C.; Martin, W. L.; Postal, R. B.; Seidel, B.; Sesplankis, T. T.; Shirley, D. L.; Stelzried, C. T.; Sweetnam, D. N.; Zygielbaum, A. I.; Esposito, P. B.; Anderson, J. D.; Shapiro, I. I.; Reasenberg, R. D.: Venus: Mass, Gravity Field, Atmosphere, and Ionosphere as Measured by the Mariner-10 Dual-Frequency Radio System. Science, vol. 183, March 29, 1974, p. 1297.

29. Sprieter, J. R.; Summers, A. L.; and Rizzi, A. W.: Solar Wind Flow Past Non-Magnetic Planets - Venus and Mars. Planet. and Space Sci., vol. 18, 1970, p. 1281.

30. Fjeldbo, G.; Seidel, B.; Sweetnam, D.; and Taylor, H.: The Mariner-10 Radio Occultation Measurements of the Ionosphere of Venus. Atmos. Sci., vol. 32, June 1975, pp. 1232-1236.

31. Whitten, R. C.; and Colin, L.: The Ionospheres of Mars and Venus. Rev. Geophys. Space Phys., vol. 12, May 1974, pp. 155-192.

32. Kumar, S.; and Hunten, D. M.: Venus: An Ionospheric Model With an Exospheric Temperature of 350° K. J. Geophys. Res., vol. 79, 1974, p. 2529.

33. Bauer, S. J.; and Hartle, R. E.: Venus Ionosphere: An Interpretation of Mariner-10 Observations. Geophys. Res. Lett., vol. 1, May 1974, pp. 7-9.

34. Noll, R. B.; and McElroy, M. B.: Models of Venus Atmosphere (1972). NASA SP-8011, Sept. 1972.

35. Kliore, A. J.; Levy, G. S.; Cain, D. L.; Fjeldbo, G.; and Rasool, S. I.: Atmosphere and Ionosphere of Venus From the Mariner-5 S-Band Radio Occultation Measurement. Science, vol. 158, 1967, p. 1683.

36. Vinogradov, A. P.; Surkov, Yu. A.; Florenyskii, K. P.; and Andreichikov, B. M.: Determination of the Chemical Composition of the Venus Atmosphere by the Venus-4 Space Probe. Soviet Physics - Doklady, vol. 13, Sept. 1968, pp. 176-179.

37. Connes, P.; Connes, J.; Benedict, W. S.; Kaplan, L. D.: Traces of HCl and HF in the Atmosphere of Venus. Astrophys. J., vol. 147, 1967, pp. 1230-1237.

38. Connes, P.; Connes, J.; Kaplan, L. D.; and Benedict, W. S.: Carbon Monoxide in the Venus Atmosphere. Astrophys. J., vol. 152, 1968, pp. 731-743.

39. Belton, M. J. S.; and Hunten, D. M.: The Abundance and Temperature of CO_2 in the Martian Atmosphere. Kitt Peak National Observatory, No. 154, 1966.

40. Broadfoot, A. L.; Kumar, S.; Belton, M. J. S.; and McElroy, M. B.: Ultraviolet Observations of Venus From Mariner-10: Preliminary Results. Science, vol. 183, March 29, 1974, p. 1315.

41. Bottema, M.; Plummer, W.; and Strong, J.: Mem. Soc. R. Sci. Liege, 1965.

42. Fink, U.; Larson, G. P.; Kuiper, G. P.; and Poppen, R. F.: Water Vapor in the Atmosphere of Venus. Icarus, vol. 17, 1972, p. 617.

43. Barth, C. A.; Pearce, J. B.; Kelly, K. K.; Wallace, L.; and Fastie, W. G.: Ultraviolet Emissions Observed Near Venus from Mariner-5. Science, vol. 158, 1967, p. 1675.

44. Kurt, V. G.; Dostovalow, S. B.; and Sheffer, E. K.: The Venus Far-Ultraviolet Observations With Venera-4. J. Atmos. Sci., vol. 25, 1968, p. 668.

45. Barth, C. A.: Interpretation of the Mariner-5 Lyman α Measurements. J. Atmos. Sci., vol. 25, 1968, p. 564.

46. Wallace, L.: Analysis of the Lyman α Observations of Venus Made From Mariner 5. J. Geophys. Res., vol. 74, 1969, p. 115.

47. Barth, C. A.; Wallace, L.; and Pearce, J. B.: Mariner-5 Measurement of Lyman α Radiation Near Venus. J. Geophys. Res., vol. 73, 1968, p. 2541.

48. Donahue, T. M.: The Upper Atmosphere of Venus: A Review. J. Atmos. Sci., vol. 25, 1968, pp. 568-573.

49. McElroy, M. B.; and Hunten, D. M.: Molecular Hydrogen in Atmospheres of Mars. J. Geophys. Res., vol. 74, Nov. 1, 1969, pp. 5807-5809.

50. Moos, H. W.; and Rottman, G. J.: OI and HI Emissions From the Upper Atmosphere of Venus. Astrophys. J., vol. 169, 1971, p. L127.

51. Pollack, J. B.; and Wood, A. T., Jr.: Venus: Implications From Microwave Spectroscopy of the Atmosphere Content of Water Vapor. Science, vol. 161, Sept. 13, 1968, pp. 1125-1127.

52. Young, A. T.: Are the Clouds of Venus Sulfuric Acid. Icarus, vol. 18, 1973, pp. 564-582.

53. Pollack, J. B.; Erickson, E. F.; Goorvitch, D.; Baldwin, B. J.; Strecker, D. W.; Witteborn, F. C.; and Augason, G. C.: A Determination of the Composition of the Venus Clouds From Aircraft Observations in the Near Infrared. J. Atmos. Sci., June 1975, to be published.

54. Surkov, Ya. A.; Andreychikov, B. M.; and Kalinkina, O. M.: Ammonia Content in the Venus Atmosphere According to Data From the Venera 8 Planetary Probe. NASA TT F-15,544, 1974.

55. Goettel, K. A.; and Lewis, J. S.: Ammonia in the Atmosphere of Venus. J. Atmos. Sci., vol. 31, April 1974, pp. 828-830.

56. Prinn, R. G.: The Upper Atmosphere of Venus: A Review. Physics and Chemistry of Upper Atmospheres, B. M. McCormac, Ed., D. Riedel Publishing Co., 1973, pp. 335-344.

57. Prinn, R. G.: Venus: Composition and Structure of the Visible Clouds. Science, vol. 182, Dec. 14, 1973, pp. 1132-1135.

58. Prinn, R. G.: Venus: Vertical Transport Rates in the Visible Atmosphere. J. Atmos. Sci., vol. 31, Sept. 1974, pp. 1691-1697.

59. Pollack, J. B.; and Sagan, C.: The Microwave Phase Effect of Venus. Icarus, vol. 4, 1965, pp. 62-103.

60. Wood, A. T.; Wattson, R. B.; and Pollack, J. B.: Venus: Estimates of the Surface Temperature and Pressure From Radio and Radar Measurements. Science, vol. 162, Oct. 4, 1968, pp. 114-116.

61. Sagan, C.: Structure of the Lower Atmosphere of Venus. Icarus, vol. 1, 1962, pp. 151-169.

62. Hunten, D. M.; and McElroy, M. B.: The Upper Atmosphere of Venus: The Regulus Occultation Reconsidered. J. Geophys. Res., vol. 73, 1968, p. 4446.

63. Eshleman, V. R.; Fjeldbo, G.; Anderson, J. D.; Kliore, A.; and Dyce, R. B.: Venus: Lower Atmosphere not Measured. Science, vol. 162, Nov. 8, 1968, pp. 661-665.

64. McElroy, M. B.: The Upper Atmosphere of Venus. J. Geophys. Res., vol. 73, 1968, p. 1513.

65. McElroy, M. B.: Structure of the Venus and Mars Atmosphere. J. Geophys. Res., vol. 74, Nov. 1, 1969, p. 29.

66. Nagy, A. F.; Liu, S. C.; Donahue, T. M.; and Atreya, S. K.: A Model of the Venus Ionosphere. Geophys. Res. Lett., vol. 2, March 1975, pp. 83-86.

67. Liu, S. C.; and Donahue, T. M.: The Aeronomy of the Upper Atmosphere of Venus. Icarus, vol. 24, 1975, pp. 148-156.

68. Fjeldbo, G.; Kliore, A. J.; and Eshleman, V. R.: The Neutral Atmosphere of Venus as Studied With the Mariner-5 Radio Occultation Experiments. Astron. J., vol. 76, March 1971, pp. 123-140.

69. Murray, B. C.; Belton, M. J. S.; Danielson, G. E.; Davies, M. E.; Gault, D.; Hapke, B.; O'Leary, B.; Strom, R. G.; Suomi, V.; and Trask, N.: Venus: Atmospheric Motion and Structure From Mariner-10 Pictures. Science, vol. 183, March 29, 1974, p. 1307.

70. Marov, M. Ya.; Avduevsky, V. S.; Kerzhanovich, V. V.; Razhdestvensky, Borodin, N. V.; and Ryabov: Venera 8: Measurements of Temperature, Pressure and Wind Velocity on the Illuminated Side of Venus. J. Atmos. Sci., vol. 30, Sept. 1973, pp. 1210-1214.

71. Traub, W. A.: Spectroscopic Observations of Motions in the Venus Atmosphere. Paper presented at the Conf. on Planet. Atmospheres, Turkey, 1972.

72. Caldwell, J.: Retrograde Rotation of the Upper Atmosphere of Venus. Icarus, vol. 17, 1972, p. 608.

73. Scott, A. H.; and Reese, E. J.: Venus: Atmospheric Rotation. Icarus, vol. 17, 1972, p. 589.

74. Woo, R.; Ishimaru, A.; and Kendall, W. B.: Observations of Small-Scale Turbulence in the Atmosphere of Venus by Mariner 5. J. Atmos. Sci., vol. 31, Sept. 1974, pp. 1698-1706.

75. Murray, B.; Wildey, R.; and Westphal, J.: Infrared Mapping of Venus Through the 8- to 14-Micron Atmosphere Window. J. Geophys. Res., vol. 68, 1963, pp. 4813-4818.

76. Ingersoll, A. P.; and Orton, G. S.: Lateral Inhomogenerties in the Venus Atmosphere: Analysis of Thermal Infrared Maps. Icarus, vol. 21, 1974, pp. 121-128.

77. Sill, G. T.: Sulfuric Acid in the Venus Clouds. Comm. Lunar Planet. Lab., vol. 9, 1972, pp. 191-198.

78. Young, A. T.: Venus Clouds: Structure and Composition. Science, vol. 183, Feb. 1, 1974, pp. 407-409.

79. Martonchik, J. V.: Sulfuric Acid Cloud Interpretation of the Infrared Spectrum of Venus. Astrophys. J., vol. 193, Oct. 15, 1974, pp. 495-501.

80. Hansen, J. E.; and Hovenier, J. W.: Interpretation of the Polarization of Venus. J. Atmos. Sci., vol. 31, May 4, 1974, pp. 1137-1160.

81. Lacis, A. A.; and Hansen, J. E.: Atmosphere of Venus: Implications of Venera-8 Sunlight Measurements. Science, vol. 184, May 31, 1974, pp. 979-982.

82. Avduevsky, V. S.; Marov, M. Ya.; Moskin, B. E.; and Ekonomov, A. P.: Venera-8: Measurements of Solar Illumination Through the Atmosphere of Venus. J. Atmos. Sci., vol. 30, Sept. 1973, pp. 1215-1218.

83. Pollack, J. B.; and Young, R.: Calculations of the Radiative and Dynamical States of Venus' Atmosphere. J. Atmos. Sci., June 1975, to be published.

84. Campbell, D. B.; Dyce, R. B.; Ingalls, R. P.; Pettengill, G. H.; and Shapiro, I. I.: Venus: Topography Revealed by Radar Data. Science, vol. 175, 1972, pp. 514-516.

85. Goldstein, R. M.; and Rumsey, H., Jr.: A Radar Snapshot of Venus. Science, vol. 169, Sept. 4, 1970, pp. 974-977.

86. Rumsey, H. C.; Morris, G. A.; Green, R. R.; and Goldstein, R. M.: A Radar Brightness and Attitude Image of a Portion of Venus. Icarus, vol. 23, 1974, pp. 1-7.

87. Saunders, S.; Friedman, L.; and Thompson, T.: Mission Planning for Remote Exploration of the Surface of Venus. AIAA Preprint 73-580, July 1973.

88. Vinogradov, A. P.; Surkov, Yu. A.; and Kirnozov, F. F.: The Content of Uranium, Thorium and Potassium in the Rocks of Venus as Measured by Venera 8. Icarus, vol. 20, 1973, pp. 253-259.

89. Muhleman, D. O.; Orton, G.; and Berge, G. L.: The Lower Atmosphere of Venus. DPS/AAS Meeting, Columbia, Md., Feb. 1975.

90. Smith, W. B.; Ingalls, R. P.; Shapiro, I. I.; and Ash, M. E.: Surface Height Variations on Venus and Mercury. Radio Sci., vol. 5, 1970, pp. 411-423.

91. Anderson, J. D.: Geodetic and Dynamical Properties of Planets. EOS, vol. 55, May 1974, pp. 515-523.

92. Bellomo, E.; Columbo, G.; and Shapiro, I.: Theory of the Axial Rotations of Mercury and Venus. Mantles of the Earth and Terrestrial Planets, S. K. Runcorn, ed., Interscience, London, 1967.

93. Lovell, J.; Born, G. H.; Christensen, E. J.; Esposito, P. B.; Jordan, J. F.; Laing, P. A.; Shogren, W. L.; Wong, S. K.; Reasenberg, R. D.; Shapiro, I. I.; and Slater, G. L.: Gravity Field of Mars From Mariner-9 Tracking Data. Icarus, vol. 18, 1973, pp. 304-316.

94. Soderblom, L. A.; Condit, C. D.; West, R. A.; Herman, B. M.; and Kreidler, T. J.: Martian Planet Wide Crater Distributions Implications for Geologic History and Surface Processes. Icarus, vol. 22, 1974, pp. 239-263.

95. Wilhelms, D. E.: Summary of Lunar Stratigraphy - Telescopic Observations. U. S. Geol. Survey Prop. Paper 599-F, 1970, 47 p.

96. Wilhelms, D. E.: Geologic Mapping of the Second Planet. U. S. Geol. Survey, Interagency Report: Astrogeology 55, 39 p.

97. Greeley, R.; and Carr, M. H., eds.: A Geologic Basis for Exploration of the Planets. 1975.

98. Wing, R. S.: Structural Analysis From Radar Imagery: Eastern Panamanian Isthmus. Mod. Geol., vol. 2, 1971, pp. 1-21 and 75-127.

99. Moore, H. T., et al.: Correlation of Photogeology and Remote Sensing Data Along the Apollo 14 Bistatic-Radar Ground Track. Part I - A Working Compendium. U. S. Geol. Surv., Interagency Report: Astrogeology 75, 1975.

100. Tyler, G. L.; and Howard, H. T.: Dual-Frequency Bistatic-Radar Investigations of the Moon With Apollos 14 and 15. J. Geophys. Res., vol. 78, 1973, pp. 4852-4874.

101. Muhleman, D. O.: Planetary Characteristics From Radar Observations. Space Sci. Rev., vol. 6, 1966, p. 341.

102. Campbell, M. J.; and Ulrichs, T.: Electrical Properties of Rocks and Their Significance for Lunar Radar Observations. J. Geophys. Res., vol. 74, 1969, p. 5867.

103. Masursky, H., et al., Television experiment for Mariner Mars 1971. Icarus, vol. 12, 1970, pp. 10-45.

104. Murray, B. C.: Imaging of the Outer Planets and Satellites. Space Sci. Rev., vol. 14, 1973, pp. 474-496.

105. Kaula, William M.: An Introduction to Planetary Physics. Chapter 2, John Wiley & Sons, New York, 1968.

106. Shapiro, I. I.; Pettingill, G. H.; Sherman, G. N.; Rogers, A. E. E.; and Ingalls, R. P.: Venus: Radar Determination of Gravity Potential. Science, vol. 179, 1973, p. 473.

107. Phillips, R. J.; and Saunders, R. S.: The Isostatic State of Martian Topography. J. Geophys. Res., vol. 80, 1975, pp. 2893-2898.

108. Evans, J. V.; and Ingalls, R. P.: Absorption of Radar Signals by the Atmosphere of Venus. J. Atmos. Sci., vol. 25, 1968, pp. 555-559.

109. MacKay, J. S.; Edsinger, L. E.; Evans, L. C.; Manning, L. A.; Sinclair, K. F.; and Swenson, B. C.: A Preliminary Analysis of a Radar-Mapping Mission to Venus. NASA TM X-2868, 1973.

110. Scofield, W. T., et al.: A Study of an Orbital Radar Mapping Mission to Venus, Vols. II and III. Martin Marietta Aerospace, NASA CR 114641, 114642, 1973.

111. Friedman, L. D.; and Rose, J. R.: Final Report of a Venus Orbital Imaging Radar (VOIR) Study. Jet Prop. Lab. Document 760-89, 1973.

112. Cutrona, J.; and Hall, G. O.: A Comparison of Techniques for Achieving Fine Azimuth Resolution. IRE Trans. Mil. Elect., MIL-6, no. 2, 1962, pp. 119-121.

113. Colin, L.; and Hall, C. F.: Pioneer Venus Orbiter Mission, Experiment Descriptions. Ames Research Center, NASA, PO-401, 1975, 43 p.

114. Friedman, L. D.; and Lewis, J. L.: Future Exploration of Venus. Astron. and Aero., May 1975, pp. 46-58.

115. Brown, W. E., Jr.; Elachi, C.; Jordan, R. L.; Laderman, A.; and Thompson, T. W.: Planetary Imaging Radar Study, Vols. I and II. Jet Prop. Lab. Document 701-145, 1972.

116. Scofield, W. T., et al.: Venus Orbital Imaging Radar (VOIR) Technical Tradeoffs Study, Vol. II. Martin Marietta Aerospace, MCR-74-276, 1974.

117. Anon.: Space Science Board Summer Study, 1974. Planetary Mission Summary: Venus Orbital Imaging Radar. Jet Prop. Lab., Calif. Inst. Tech. SP 43-10, vol. 12, 1974, pp. 1-11.

118. Seiff, A.; Sommer, S. C.p Kirk, D. B.; and Blanchard, R. C.: Atmosphere Structure Experiment. Pioneer Venus Multiprobe Mission, Experiment Descriptions, 1974, p. 17.

119. Leovy, C. G.: Rotation of the Upper Atmosphere of Venus. J. Atmos. Sci., vol. 30, Sept. 1973, p. 1218.

120. Mellor, J. W.: A Comprehensive Treatise on Inorganic and Theoretical Chemistry, Vol. I. Longmans, Greene and Co., London, New York, and Toronto, 1930, pp. 397-401.

121. Lewis, J. S.: An Estimate of the Surface Conditions of Venus. Icarus, vol. 8, 1968, p. 434.

122. Dayhoff, M. O.; Lippincott, E. R.; Eck, R. V.; and Nagarajan, G.: Thermodynamic Equilibrium in Prebiological Atmospheres of C, H, O, N, P, S, and Cl. National Biomedical Research Foundation and U. of Md., NASA SP-3040, 1967.

123. Rubey, W. W.: Geologic History of Sea Water. Bull. Geol. Soc. Am., vol. 62, 1951, p. 1111.

124. Reynolds, S. E.; and Brook, N.: Correlation of the Initial Electric Field and the Radar Echo in Thunderstorms. J. Met., vol. 13, 1956, p. 376.

125. Sartor, J. D.: Some Electrostatic Cloud-Droplet Collision Efficiencies. J. Geophys. Res., vol. 65, 1960, p. 1953.

126. Lacis, A. A.: Cloud Structure and Heating Rates in the Atmosphere of Venus. J. Atmos. Sci., vol. 32, June 1975, p. 1107.

127. McElroy, M. B.; Nien Dak Sze; and Yuk Ling Yung: Photochemistry of the Venus Atmosphere. J. Atmos. Sci., vol. 30, Oct. 1973, p. 1437.

128. Seiff, A.: Direct Measurements of Planetary Atmospheres by Entry Probes. Advances in the Astronautical Sciences; vol. 25, Advanced Space Experiments, O. Tiffany and E. Zaitzeff, eds., Feb. 1969.

129. Lewis, J. S.: Origin and Chemistry of the Venus Atmosphere. Pioneer Venus - Report of a Study by the Science Steering Group, 57, June 1972.

130. Eggers, A. J., Jr.: The Possibility of a Safe Landing. Chapter 13 of Space Technology, H. S. Seifert, ed., John Wiley & Sons, New York, 1959.

131. Seiff, A.; and Tauber, M. E.: Minimization of the Total Heat Input for Manned Vehicles Entering the Earth's Atmosphere at Hyperbolic Speeds. NASA TR R-236, May 1966.

132. Short, B. J.: Newtonian Aerodynamics for Circular Cones Modified to Produce Lift at Zero Angle of Attack. NASA TN D-5193, May 1969.

133. Chalmers, J. A.: Atmospheric Electricity. Pergamon Press, New York, 1967.

134. Reiter, R.: A Contribution to the Atmospheric-Electric Phenomenology of Non-Thunderstorm Clouds and Precipitations. Vol. 2 of Planetary

Electrodynamics, S. C. Coroniti and S. Hughes, eds., Gordon and Breach Science Publishers, New York, 1969, pp. 59-81.

135. Fitzgerald, D. R.; and Byers, H. R.: Aircraft Observations of Convective Cloud Electrification. Recent Advances in Atmospheric Electricity, L. G. Smith, ed., Pergamon Press, New York, 1958, pp. 245-268.

136. Workman, E. J.: The Production of Thunderstorm Electricity. J. Franklin Institute, vol. 283, 1967, pp. 540-557.

137. Takeuchi, T.; Muhleisen, R.; and Fischer, H. J.: Some Observations on Charge Generation in Thunderclouds. Planetary Electrodynamics, S. C. Coroniti and S. Hughes, eds. Vol. 1, Gordon and Breach Science Publishers, New York, 1969, pp. 395-399.

138. Larsen, H. R.; and Stansbury, E. J.: Association of Lightning Flashes With Precipitation Cores Extending to Height 7 km. J. Atm. and Terrestrial Phys., vol. 36, 1974, pp. 1547-1553.

139. Schaefer, V. J.: The Electrification of Oil and Water Clouds. Recent Advances in Atmospheric Electricity, L. G. Smith, ed., Pergamon Press, New York, 1958, pp. 431-434.

140. Baxter, J. F.; Frank, R. E.; Froistad, J. N.; and Cody, G. R.: Buoyant Venus Station Feasibility Study for 1972-1973 Launch Opportunities, Vol. 1, Mission Summary Definition and Comparison. Martin Marietta Aerospace, NASA CR-66725-1, 1969.

141. Marquet, D. W.; and French, C. E.: Buoyant Venus Station Feasibility Study for 1972-1973 Launch Opportunities. Vol. II, Trajectory Analysis. Martin Marietta Aerospace, NASA CR-66725-2, 1969.

142. Carroll, P. C.; and Deats, C. L.: Venus Balloon Systems. Eighth AFCRL Scientific Balloon Symposium, 1974.

143. Carroll, P. C.; Frank, R. E.; and Pettus, J. D.: Buoyant Venus Station Feasibility Study for 1972-1973 Launch Opportunities. Vol. III, Part I, Configuration. Martin Marietta Aerospace, NASA CR-66725-3, 1969.

144. Barger, A. R., et al.: Buoyant Venus Station Feasibility Study for 1972-1973 Launch Opportunities. Vol. III, Part II, Appendices. Martin Marietta Aerospace, NASA CR-66725-4.

145. Anon.: Delta Class Balloon and Lander Missions for the Exploration of Venus. Martin Marietta Corp., Denver, Colorado, MCR 70-211, 1970.

146. Anon.: Venus Balloon Mission Study. Martin Marietta Corp., Denver, Colorado, MCR 73-248, CNES Contract 1808, 1973.

147. Anon.: 1975 Venus Multiprobe Mission Study, Vols. I and II. Martin Marietta Corp., Denver, Colorado, MCR 70-89, JPL Contract 952534, 1970.

148. Vinogradov, A. P.; Surkov, Yu. A.; and Kirnozov, F. F.: The Content of Uranium, Thorium and Potassium in the Rocks of Venus as Measured by Venera 8. NASA TT F-14,911, 1973.

149. Lewis, J. S.: Metal/Silicate Fractionation in the Solar System. Earth Planet. Sci. Letters, vol. 15, 1972, pp. 286-290.

150. Lewis, J. S.: Volatile Element Influx on Venus From Cometary Impacts. Earth Planet. Sci. Letters, vol. 22, 1974, pp. 239-244.

151. Arrhenius, Gustaf: Boundary Conditions on Atmospheric Evolution. The Atmosphere of Venus, Conf. Proceedings, Goddard Institute for Space Studies, 1974, pp. 181-187.

152. Fricker, P. E.; and Reynolds, R. T.: Development of the Atmosphere of Venus. Icarus, vol. 9, 1968, p. 221.

153. Sagan, C.: The Radiation Balance of Venus. JP.-CIT Tech. Rept., 1960, pp. 32-34.

154. Avduevsky, V. S.; Marov, M. Ya.; and Rozhdestvensky, M. K.: A Tentative Model of the Venus Atmosphere Based on the Measurements of Venera 5 and 6. J. Atmos. Sci., vol. 27, 1970, p. 561.

155. Oberbeck, V. R.; and Quaide, W. L.: Genetic Implications of Lunar Regolith Thickness Variations. Icarus, vol. 9, 1968, p. 446.

156. Adams, J. B.: Visible and Near-Infrared Diffuse Reflectance Spectra of Pyroxenes as Applied to Remote Sensing of Solid Objects in the Solar System. J. Geophys. Res., vol. 79, 1974, p. 4829.

157. Öpik, E. J.: Mariner IV and Craters on Mars. Irish Astron. J., vol. 7, 1965, pp. 92-104.

158. Hartmann, W. K.: Martian Cratering, Mariner 9 Initial Analysis of Cratering Chronology. J. Geophys. Res., vol. 78, 1973, pp. 4096-4116.

159. Chapman, C. R.: Cratering on Mars. II. Cratering and Obliteration History. Icarus, vol. 22, 1971, pp. 272-291.

160. Chapman, C. R.: Cratering on Mars and Obliteration History. Icarus, vol. 22, 1974, pp. 272-291.

161. Jones, K. L.: Evidence for an Episode of Crater Obliteration Intermediate in Martian History. J. Geophys. Res., vol. 79, 1974, pp. 3917-3931.

162. Arvidson, R. E.: Morphologic Classification of Martian Craters and Some Implications. Icarus, vol. 22, 1974, pp. 264-271.

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